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Overheating Prevention and Daylighting in Buildings without Mechanical Cooling

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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 doctoral or equivalent academic degree.

Raimo Simson

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Ülekuumenemise vältimine ja loomuliku valguse tagamine mehaanilise jahutuseta hoonetes

RAIMO SIMSON

TALTECH KIRJASTUS

Contents

List of Publications

This thesis is based mainly on data presented in the following peer-reviewed journal and conference publications:

I Simson, R., Kurnitski, J., Maivel, M. 2016. Summer Thermal Comfort: Compliance Assessment and Overheating Prevention in New Apartment Buildings in Estonia. Journal of Building Performance Simulation, 10 (4), 378-391. DOI:10.1080/ 19401493.2016.1248488

II Simson, R., Kurnitski, J., Kuusk, K. 2017. Experimental validation of simulation and measurement-based overheating assessment approaches for residential buildings. Architectural Science Review, 60 (3), 192-204. DOI:10.1080/00038628.2017. 1300130

III Simson, R., Voll, H., Tamm, K., Kurnitski, J. 2019. Daylight, Sunlight and Overheating Conflicts and Control with Shading Balconies in Residential Buildings. Indoor and Built Environment [Submitted for publication, 7.10.2019].

IV Kiil, M., Simson, R., De Luca F., Kurnitski J. 2019. Overheating and Daylighting Evaluation for Free-running Classroom Designs. Nordic ZEB 2019: 1st Nordic conference on Zero Emission and Plus Energy Buildings. IOP Conf. Series: Earth and Environmental Science, 352, 012059. DOI:10.1088/1755-1315/352/1/012059

V De Luca, F., Kiil, M., Simson, R., Kurnitski, J., Murula, R. 2019. Evaluating Daylight Factor Standard through Climate Based Daylight Simulations and Overheating Regulations in Estonia. Proceedings of Building Simulation 2019: 16th Conference of IBPSA. Sept 2-4 Rome, Italy.

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

Author’s Contribution to the Publications

The author of the thesis is the principal author of publications I, II and III. In IV and V the author of the thesis is responsible for partial analysis and for writing parts of the manuscript. In I and II data collection, measurements, simulations, calculations and analysis were carried out by the author. In III parts of the simulations and analysis were performed by the author. The research principles of the study were developed together with the co-authors. The manuscripts of papers I, II and III were composed by the author.

Introduction

With the goals set by the Energy Performance of Buildings Directive (EPBD) [1] energy performance of buildings has been greatly improved. Even with lower energy usage, healthy indoor climate must be provided, as is stressed in the revised EPBD.

As of 2019, all new buildings in the Estonian public sector are built as nearly-zero energy buildings (nZEB), all remaining building types from 2021 and existing buildings to be transformed to nZEB by 2050. To meet the energy performance requirements, such buildings have highly insulated airtight envelopes, and often large glazed surfaces following an architectural trend, which allow and trap excessive solar radiation into the interior space. As a result, these buildings often experiencing unacceptably high temperatures that make it impossible to use the building not only during summer periods but also during spring and autumn. Unless mechanical cooling is used, overheating becomes an increasingly common problem, even in temperate and cold climate countries.

In residential buildings, the issue is especially problematic in apartment buildings, where adaptation is more difficult than in detached and terraced houses. High indoor temperatures occur not only in residential but often also in non-residential building types. As school buildings in Estonia are also built without the use of mechanical cooling systems, overheating in classrooms especially during spring and autumn is an increasingly appearing problem.

When overheating prevention requirements came into force first time in 2008 in Estonia these were often not considered seriously or neglected because the evaluation requires dynamic computer simulations and control over the calculations was in practice non-existent. In an increasing number of cases, the developer of a building was forced to take measures to combat overheating problems in existing or newly constructed buildings to avoid going to court. Therefore, learning from mistakes was a common way how these requirements established in practice in a couple of years.

Technically, predicting overheating is a complex task, it requires detailed information about the building and its use – its construction elements, thermal mass, glazing elements, airtightness, heating and ventilation systems, occupant behaviour, internal heat gains, etc. There is a lot of uncertainty in occupant behaviour, including window opening habits, equipment usage, heat gain assessment, warmer and colder summers, etc. Despite that, it is necessary to adequately predict room temperatures of the building at the design stage, before the construction begins, because dealing with the consequences of the problem is generally costly and technically difficult. Temperature simulations at the planning stage need that the standard use of the building is defined including for instance window opening which has resulted in complex and time-consuming simulations requiring the competence of an experienced energy specialist. This stresses a need for a sufficiently simple and clear future-proof method to assess overheating in new building design as well as in existing buildings with acceptable precision. For this purpose, the analysis of effective passive solutions is needed to prevent overheating by limiting the external heat gains and dissipating and removing the excess heat.

As long winters in temperate climate regions dominate the yearly cycle, allowing direct sunlight and increasing daylight availability during springtime in indoor spaces, specifically in dwellings, is proven to have a positive effect on occupant’s wellbeing. Sufficient daylighting is considered mandatory and regulated in many countries as a requirement in building design. In Estonia, separate regulations govern requirements for daylighting and overheating prevention. The calculation methodology for insolation duration does not account for fixed external shades, making it difficult or even impossible to fulfil the required criteria. Thus, the colliding requirements leave little room for suitable, sustainable façade design options.

In classrooms, occupants' thermal and visual comfort is directly related to lighting conditions, especially to the availability of daylight. Sufficient daylighting can improve students' learning performance and also increase the energy efficiency of the building by reducing electrical lighting use. In contrast to dwellings, direct sunlight in classrooms can have a negative impact on thermal and visual conditions, as it produces unwanted heat gains contributing to overheating, but also glare and reflections, and is recommended to avoid. Therefore, it is vital to properly design classroom facades by allowing sufficient daylight into the room and blocking excess sunlight, thus reducing overheating risk.

The main objectives of the thesis are:

- To map the current situation regarding summertime indoor temperatures and overheating in new residential buildings without mechanical cooling systems (I)
- To analyse the main factors contributing to overheating risk in existing buildings and to determine passive solutions which can effectively prevent overheating (I)
- To assess the compliance with national regulations of existing residential buildings for an overview of the effect of the current building code in practice (I)
- To analyse which properties will make a room 'critical', i.e. most likely overheated, to be chosen for compliance assessment procedure (I)
- To analyse and further develop the current compliance assessment methodology, regarding its suitability of temperature-based simulations (I, II)
- To analyse the impact of modelling detail and thermal zoning options as a single-zone vs full apartment for the development of an alternative option for the overheating assessment method (II)
- To develop a method for overheating risk assessment in existing buildings based on measured data (II)
- To analyse the effect of shading balconies on indoor temperatures, daylighting and insolation in dwellings (III)
- To find optimal solutions for classroom designs which ensure sufficient daylighting and overheating prevention at the same time (IV, V)

To achieve the objectives, the following methods were used:

- On-site temperature measurements and building parameters data collection
- Dynamic computer simulations to estimate indoor temperatures and daylighting
- Overheating assessment, daylighting and insolation analysis by appropriate methodology
- Sensitivity analysis of building parameters and shading elements

The thesis is based on peer-reviewed journal and conference articles.

In article I we have analysed the issues of summer thermal comfort and compliance assessment of new buildings. We have taken indoor temperature measurements in 18 living rooms and bedrooms from 16 different apartment buildings during the summer period of 2014. For compliance assessment of the studied buildings, we have simulated indoor temperatures in chosen rooms most likely to encounter overheating problems. In total, 158 rooms from 25 buildings were simulated. The results from measurements and simulations are used to identify the 'critical room' defining parameters and to find out, which design measures used in practice can effectively reduce the risk of overheating in Estonian climate and latitude.

In article II we have analysed the impact of thermal zoning on the simulation-based overheating assessment calculation and to give a temperature measurement-based "rule of thumb" for a low-cost method for pre-assessing overheating compliance of dwellings. We have compared measured hourly average indoor temperature with results from three levels of thermal zoning – the currently used single-zone method and two multi-zone approaches: whole apartment and whole building model approach. For detailed analysis, we have selected apartments from five apartment buildings in which temperature measurements have been conducted during the summertime period of 2014. To compare the calculation methods for summer thermal comfort assessment, we have calibrated the simulation results using the temperature measurements.

In article III we have analysed daylighting and overheating risk of a modern apartment building in Estonia. The main focus is on static shading elements – balconies with opaque overhangs, railings and side-fins. We have conducted indoor temperature simulations according to the Estonian building regulations and daylighting assessment according to national and European standards. The paper addresses the shortcomings of the calculation methods and proposes improvements to the current methodology for daylighting assessment considering summertime overheating prevention by the use of shading balconies.

In articles IV and V, we have investigated overheating and daylight performance of classroom and facade design variations for different floor dimensions, window sizes, glazing parameters and shading use. We have found optimal solutions that fulfil daylight and overheating prevention requirements for classroom design.

Practical outcomes and novelty of the thesis:

- The results and outcomes of the research have been used as input in the revised national regulations No 63 'Minimum requirements for energy performance' and No 58 'Methodology for calculating energy performance of buildings' in 2018, in force as of 2019. Based on the research, guidelines for 'assessing and preventing overheating in residential buildings' have been published, intended to assist building energy specialists, architects and engineers during the preliminary building design process.
- Overheating analyses in I resulted in overheating prevention passive solutions which were possible to generalize with a new formula including window to wall ratio and solar factor of shadings and glazing.

- Overheating assessment methodology development in II made a new scientific contribution by showing that an alternative multi-zone method resulted in more close agreement of measured and simulated temperatures whereas an existing single-zone method proved to be a safe side conservative method. Analyses in II produced a new formula which allows scaling the measured overheating temperatures and temperature excess to the value applying with test reference year which is used in compliance assessment methodology. This formula cannot be used for the compliance assessment by measurements but by showing a link between measured and simulated temperatures using different weather data it proves that the official methodology has solid bases.
- Sunlight and daylight analyses in III showed a conflict between insolation and overheating requirements and provided new scientific evidence that insolation analyses are sufficient for a fixed day instead of a long time period.
- Holistic classroom façade and ventilation analyses in IV and V resulted in new scientific evidence that passive design is possible in modern buildings in Estonian climate and which technical solutions are most appropriate in order to meet overheating prevention and daylighting criteria.

Limitations of the work:

- The work is based on, and accounts for specific methods, climate, building properties and architecture of new buildings which are typical to Estonia.
- The many aspects of different metrics and dynamics of both natural lighting and occupant behaviour, perception and uncertainties, including specifics of thermal comfort, occupants adaptivity, quality and variations in lighting conditions etc, are not analysed or discussed in detail and existing health and comfort criteria are used for natural light and thermal comfort.
- The present work does not discuss the aspects of whole-year energy performance of buildings which are affected by the design implementations for managing overheating risk and daylighting, including aspects of energy use for heating and lighting. Proposed technical solutions for overheating and natural light control generally improve energy performance if properly used, but these effects are not quantified and analysed.
- The study does not consider future climate projections or the dynamics of dense cities in regard to urban heat islands.
- The analysis of school buildings is limited only to preliminary assessment of typical classroom configurations and based on simplified approach regarding façade designs with pre-determined windows and shading options.

Notations

Abbreviations

AHU	Air Handling Unit
CV	Coefficient of Variation
CV(RMSE)	Coefficient of Variation of the Root Mean Squared Error
DF	Daylight Factor
DH	Temperature excess in Degree-Hours
EN	European Standard
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
EU	European Union
EN	European Standard
EVS	Estonian Standard
HVAC	Heating Ventilation and Air Conditioning
IC	Indoor Climate
IDA ICE	IDA Indoor Climate and Energy
MBE	Mean Bias Error
mDF	Mean Daylight Factor
MET	Metabolic Rate
nZEB	Nearly zero-energy building
OA	Openable Area divided by the total area of windows
RMSE	Root Mean Square Error
SD	Standard Deviation
TRY	Test Reference Year
VT	Visible Transmittance
WFR	Window-to-Floor Ratio
WWR	Window-to-Wall Ratio

Symbols

A	Area, m^2
B	Side-fin depth, m
C	Length, m
d	Wall thickness, mm
g	Solar factor, -
H	Height, m
L	Overhang depth, m
P	Probability value, -
q_{50}	Air leakage rate of building envelope at 50 Pa pressure difference, $m^3/(h \cdot m^2)$
R^2	Coefficient of determination, -

U	Thermal transmittance, W/(m^2·K)
t	Temperature, °C
t_b	Base temperature for temperature excess calculation, °C
$t_{b,n,\mathrm{corr}}$	Corrected base temperature for given year n, °C
t_{cool}	Cooling setpoint, °C
α_a	Acceptance (solar) angle, °
α_s	Solar azimuth, °
γ_s	Solar altitude, °
Δt	Temperature deadband, K
z	Building height factor, -
Θ	Visible sky angle, °

Subscripts

g	glazing
tot	total
r	critical
corr	corrected
min	minimum
max	maximum

Terms

Overheating	Discomfort to occupants caused by the accumulation of warmth within a building, quantified here as temperature excess over a threshold value
Temperature excess, DH_{tb} (Kh)	The sum of degree-hours over a base temperature calculated for a period of time
Degree-hour (unit) Kh or °Ch	Number of degrees Kelvin (or Celsius) by which the hourly average indoor temperature is below or above a base temperature
Base temperature t_b, (°C)	A temperature value set as a threshold over which to calculate temperature excess
Insolation	Sunlight exposure, exposure to the sun's rays
Daylight	The visible part of global solar radiation
Thermal comfort	The condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation
Mechanical cooling	Lowering the temperature within a space using refrigerant compressors or absorbers, desiccant dehumidifiers, or other systems that require energy from depletable sources to directly condition a space

1 Background

1.1 Summer thermal comfort and overheating in buildings

The definition of 'Thermal comfort' is given as 'that condition of mind which expresses satisfaction with the thermal environment' [2]. Fanger [3] has identified six fundamental factors contributing to human thermal comfort: temperature, relative humidity, thermal radiation, air relative velocity, metabolic rate and clothing insulation. Some of these parameters are relatively easy to assess, maintain and measure with satisfying accuracy (e.g. temperature); for others (e.g. predicting metabolic rate or clothing), it may prove difficult or impossible. The addition of the variability in individual perception of comfort makes defining any specific criteria or threshold for uncomfortable or unacceptable comfort levels, in the context of buildings, complex and challenging. In a recent overview of thermal comfort studies [4] researchers have emphasized the importance of mean radiant temperature on occupants' thermal comfort – improving operative temperature and radiant asymmetry improves thermal comfort [5].

There have been various indices and scales used to assess summertime thermal comfort and heat stress through indoor temperature [6, 7]. Overall, more than 70 indices and metrics have been suggested for quantifying discomfort to occupants caused by the accumulation of warmth within a building to define the room or building as 'overheated' [8]. For example, based on the concept of adaptive, as opposed to Fanger's static thermal comfort, the European standard EN 15251 [9] gives a maximum allowable difference from comfort temperature. On the other hand, the CIBSE Environmental Design Guide A [10] suggests a benchmark approach be used, where the summer thermal performance of the building is measured against a temperature that should not be exceeded for a defined number of hours or percentage of the occupied hours. These single temperature exceedance threshold criteria are usually developed for a specific population or geographic location and may not apply to other regions with different climatic conditions. As air temperature is regarded as one of the most important parameters regarding human thermal comfort [11], easy to comprehend and measure, many other overheating criteria are based on the room temperature duration over a threshold value in a given time.

Historically, in cold climate countries, the need for cooling in many building types has proven unnecessary because of the building's architecture, usage, internal heat gains and building envelope properties. The most common building types that fall into this category are residential buildings, day-care centres and school buildings. It is also proven that occupants in these building types are most vulnerable to overheating [12-16].

In residential buildings, there are differences regarding typical occupied hours in living rooms and bedrooms, and differences in occupant clothing and activity levels, which are accounted in some guidelines, for example, the CIBSE Guide A adaptive comfort criteria [10], which gives different approaches for living rooms and bedrooms. Several large-scale studies have showed that there are no distinct differences in mean temperatures in living rooms and bedrooms during day time and night time [17, 18], thus same criteria has been often used on both room types with a static thermal comfort criterion. As guidelines, standards and regulations deal only with spaces that are assumed by default as frequently used, such as bedrooms and living rooms, no clear difference regarding thermal comfort in other rooms, for example, kitchens and dining rooms, has been made.

During the last five years, there have been several large-scale studies carried out in Estonia, with the focus on the technical condition and indoor climate of the residential building stock [19]. Although most of the studied buildings were built before the 1990s, a considerable sample of newer buildings with construction year between 1990 and 2010 was also included. It was found that indoor temperatures exceed the criterion for overheating in 63% of the studied dwellings. Maivel, Kurnitski and Kalamees [18] investigated indoor temperature-related problems in old and new apartment buildings in Estonia and found that overheating is most common in new buildings. Problems with high indoor temperatures have been reported also in other cold climate regions. In Sweden, occupants in retrofitted [20] and low-energy buildings [21] have complaints about high temperatures in the summer.

1.2 High temperatures and heat stress effects on occupants' health

Human well-being and health are directly affected by the increase in temperature over the comfort levels [22]. High ambient temperatures can have a substantial influence on occupants' thermal comfort in buildings. With hot weather days contributing to building overheating, the resulting heat stress can cause an increase in the occurrence of morbidity and mortality [23, 24]. Prolonged periods of extremely hot weather, defined as 'heatwaves' are testing buildings to cope with the severe external conditions [15]. It was estimated over 70 000 excess deaths in Europe during summer heatwave of 2003 [25] and over one-half of the excess deaths during these events are because of cardiovascular mortality [26].

In Estonia, the mortality rate during the summer months in 2010 was estimated 30% higher than the expected rate because of hot weather [27]. By 2100 the average annual temperature is predicted to rise between 2.7...4.3K and the occurrence of high-temperature extremes will become more frequent [28, 29]. By 2050 it is predicted over 2.5 times mortality increase because of extreme weather events in the UK [30, 31]. These extreme heatwaves will further increase health problems, heat strokes and morbidity rate is not only most vulnerable people, including infants and elderly [26, 30].

The problems with summer overheating and its effects on occupants in colder climate regions have not been an issue before or have been ignored in the Building regulations in most countries [32]. This is mainly because of the insufficient know-how amongst architects, designers and engineers in preventing and addressing these problems and adapting to the changes in buildings and regulations [16, 33].

1.3 Daylight and sunlight in buildings

Achieving a balance between thermal and visual comfort is one of the key aspects especially in buildings without mechanical cooling, in terms of low heating energy need, low risk of overheating and sufficient direct sunlight and daylighting [34-36]. In moderate and cold climate countries, maximizing the utilization of solar heat gains during the heating season can benefit substantially in lowering the heating need [37-39].

Apart from energy efficiency and thermal comfort, urban planning and building designs need also account for overshadowing to assure sufficient daylighting and direct sunlight [40-42]. As natural light has a positive effect on occupants' comfort [43-45], it is emphasized as part of sustainable building design [46]. Research shows that daylight variability during days and seasons and day-night cycles improve the well-being of occupants and their circadian rhythm [47, 48]. Daylight is the most appreciated source of illumination for building interiors of every typology for its capacity to render surfaces and objects without altering colours, to create contrasts which generate architecture quality and to be diffused in-depth into the floor plan [49]. Daylight can be available from different sources: direct solar radiation, diffused by sky and clouds and reflected by the surroundings. Direct solar radiation is the most appreciated source of daylighting for its quantity, quality and distribution potential, especially for residential premises [49-51]. Studies on lighting conditions show positive effects of natural light availability on performance and visual comfort [44, 52]. In commercial, office or school buildings, daylight is useful because its availability mostly coincides with the hours during which buildings are used [50]. The effects of lighting conditions in classrooms on schoolwork performance are relatively well researched [12, 14, 52-54] The use of daylight through windows and skylights is proved to be associated with improved student learning performances [55]. Window-to-Wall Ratio of minimum 20% proved to be the most significant daylight feature in classrooms for the improvement of student tests performance [56].

Different methods have been developed to predict building interiors daylight levels, with the use of models and formulas or computer simulations [57]. Daylight Factor (DF) is a long-standing metric which estimates the potential natural illumination of an interior point as a percentage of the illuminance of an unobstructed point on the exterior of the room [58]. DF takes into account room size and layout, windows size and position, external obstructions, materials reflectance and glazing transparency. It is an efficient metric because of its simple calculation method fast to perform through computer simulations. The limitation of DF calculation lies in not taking into account building location, climate and orientation. In recent years researchers developed new climate-based annual daylight metrics to predict accurately the quantity of illuminance and daylight autonomy in relation to threshold values [59, 60].

Daylight utilization is an efficient way to save energy related to electric lighting [61] and heating [62] in school buildings, as its availability corresponds to the period during which buildings are occupied. Thus, daylighting is an important factor in classroom planning and school building design. At the same time, excessive direct solar access can cause unwanted glare and solar heat gains that influence occupants' comfort and building energy use because of cooling need during warm periods also at northern latitudes [63, 64]. As high indoor temperature has a negative effect on learning ability [12, 54, 65], it is essential to assess buildings in early stages of design development to properly ensure sufficient daylighting and prevent overheating.

In Estonia, daylight in buildings is regulated by the standard Daylight in dwelling and Offices [66]. The standard sets different minimum mean Daylight Factor (mDF) values for a series of internal spaces of buildings, of which classrooms are required to guarantee a minimum of 2% mDF. Overheating assessment for new buildings in the design stage is required by the National Building Code by using a temperature excess calculation method, based on dynamic indoor temperature simulations [67]. Recent studies show that there are conflicts in regulations and standards developed to regulate the design of building envelopes urban planning [36, 68].

1.4 Façade design impact on buildings without mechanical cooling

Sustainable low-energy building design requires sophisticated analysis and cooperation between every party included, starting from architects, energy efficiency specialists and HVAC engineers [69]. It is vital that optimizing building performance to ensure low energy consumption must not compromise good indoor climate. However, with the trends in architecture and envelope design, an increasing number of low-energy buildings are built with a tendency to overheat [70-73]. Overheating has become a common problem also in temperate and cold climate countries [18, 21, 74-76]. As the design implications mostly consider heating, such as the passive house standard, can cause unacceptably high indoor temperatures in warmer seasons [15, 21, 77-79].This is especially the case in new residential [71, 80, 81] and school buildings [82-84] with improved air tightness, higher levels of insulation, large glazing areas and lack of mechanical cooling [85].

In terms of passive cooling solutions, a framework of three steps can be stated: heat gains prevention, heat gains modulation and heat dissipation. Kim et al. [86] have assessed the thermal performance of external shading devices and found that from the conventional shading devices, overhangs or light-shelves can have the highest effect on cooling load reduction. From the conventional shading devices, overhangs or light-shelves can have the highest effect on solar heat gains reduction [86]. It has been shown that with the combination of proper design of building elements and static shades, it is possible to assure comfortable indoor air temperature throughout the year and to avoid overheating in summer [87-94]. Regarding future climate projections, Porritt et al. [95] concluded that overheating could be avoided, amongst other passive means, with the use of external window shutters. Apart from façade shading elements, sufficient ventilation and foliage shading – especially higher trees – can have a substantial effect on indoor temperature [92].

1.5 Modelling and simulations in indoor climate analysis

With the introduction and development of building simulation tools, the use of thermal modelling has continuously grown in the last decades and has gained much importance as a part of the building design phase [96]. The evolution of these software environments and increase in computing power, more detailed and advanced models can be created and analysed, to imitate real buildings in operation. Aside from energy consumption estimation, accurate and detailed simulations of indoor climate parameters have been made possible [97]. Simulation-based assessment of planned buildings energy consumption has become a vital part of Standards and Building codes. With the help of the new Energy Performance of Buildings Directive (EPBD), some progress regarding the implementation of the procedures for providing summer thermal comfort assessment strategies has been made.

Assessing the risk of overheating in buildings can be a rather difficult and time-consuming task. Using detailed dynamic simulations is becoming the mainstream method practised among architects and specialists, with also raising trends in analysing buildings, where mechanical cooling systems are not foreseen. There are, however, many important variables causing differences between real situation and assessment results, such as occupant behaviour [98], occupancy density and patterns in terms of internal gains, opening and closing windows [99], shading and air movement dynamics, which are difficult to predict [100]. To reduce the complexity of such analysis, some forms of standardized methods are practised in different parts of the world [32]. For example, in the UK, a simplified static calculation assessment method can be used for residential developments [32, 101, 102], in Finland on the other hand, multi-zone dynamic simulations are required by the Building Code [103]. Using the more complicated simulations to predict overheating with acceptable accuracy requires sufficiently detailed modelling with adequately defined thermal zoning, especially in case of low-energy and free-running buildings [104]. Simplifications in such thermal modelling and calculations are welcomed among building professionals [105], but can only to be stretched to a reasonable extent to estimate building performance with an acceptable margin of error. Drawbacks of using such simplified approaches have been also recently reported [32, 106].

1.6 Requirements in building performance assessment

There are different methods to estimate both overheating risk [32, 107, 108] and daylighting performance [59, 109, 110] of buildings in the design phase. As most commonly acknowledged standardized methods only govern one or the other [111], it is also a common practice to analyse visual and thermal comfort assessment separately. Daylight is usually assessed by computer simulations or by mathematical models for simpler cases, such as single-room calculations. Recent studies have shown the importance of choosing a suitable daylighting design [110, 112-115] and calculation method [110, 116, 117] by critically reviewing and comparing design principles, strengths and weaknesses of different ranges of daylighting systems, assessment methods and metrics. It is essential to ensure that excessive daylighting would not pose thermal discomfort to occupants [112]. In the European Union Member States, daylight requirements or recommendations mainly specify a minimum share of window or glazing area per floor area (WFR), show minimum levels for daylight or stipulate the need for sunlight access in buildings and a view to the outside [118].

Estimating overheating risk is more complicated and, in most cases, requires dynamic computer simulations [32, 119, 120]. To assess the levels of thermal comfort in dwellings, a compliance regulation has been launched in Estonia – 'Minimum requirements of Energy Performance' [121] – to meet its obligations after the adoption of the EPBD directive [1] that required the Member States to provide a standard assessment procedure for evaluating the likelihood of overheating, during the everyday performance of new buildings and major building renovations. The new regulation states that all buildings, which have acquired a construction permit after the year 2009, are required to comply with this regulation, which also regulates the verification of summer thermal comfort compliance in buildings. The compliance verification procedure is given in detail in regulation No. 63, 'Methodology for calculating the energy performance of buildings' [122]. According to the Regulation, the compliance verification calculation for summer thermal comfort in residential buildings needs to be conducted for at least one living room and one bedroom, with the highest risk of overheating. As opposed to the Finnish multi-zone methodology, for example, the Estonian approach implies single room calculations, in which the heat and air transfer dynamics of the apartment or the building as a whole are not accounted.

2 Methods

In this chapter, description of the methods, climate data, studied buildings, conducted measurements, modelling and simulations are given. The following sections summarize the process and steps of the work.

The first task was to map the current situation regarding summertime indoor temperatures and overheating in new residential buildings which are built without mechanical cooling systems. To achieve this, indoor temperature measurements in 22 dwellings located in the selected 16 apartment buildings were conducted during the summer months of 2014. The temperature measurement results were analysed and temperature excess (DH) from the measured hourly temperature values was calculated for each of the measured dwelling. The DH values were used to analyse the main factors contributing to overheating risk and to determine the preliminary passive solutions which can prevent overheating in existing buildings. Description of the analysed buildings is presented in chapter 2.4 and the results are presented in chapter 3.1.

The next step was to assess the compliance with national regulations of existing residential buildings for an overview of the effect of the current building code in practice. In total 25 buildings were analysed, including the 22 buildings in which the temperature measurements were conducted. Description of the analysed buildings is presented in chapter 2.4. Altogether 158 rooms were simulated as required by the national methodology for assessing overheating by using Test Reference Year (TRY) climate data. The workflow of the standardised methodology is presented in Figure 1 (showed with the dashed line boundary). From the simulated indoor temperatures, DH values were calculated and used to analyse effective measures for overheating prevention and to define which properties will make a room ‘critical’, i.e. most likely overheated, to be chosen for compliance assessment procedure. The latter results, including a comparison of DH between standardised simulation results and real year measurements, are presented in chapter 3.4.

To analyse the current compliance assessment methodology and the impact of modelling detail and thermal zoning, five buildings were modelled in higher detail than required in the national regulation for overheating assessment. The case study buildings are described in chapter 2.4.2. Only for the specific analysis of the five buildings a calibration procedure was conducted as described in chapter 2.6.3. The workflow for the calibration process is shown in Figure 1. For this purpose, weather data for the year 2014 acquired from the Estonian Weather Service (EMHI) [123] was used. The calibration results are shown in chapter 3.2.1 and the results for thermal zoning impact are presented in chapter 3.2.2. To develop a method for overheating risk assessment in existing buildings based on measured data, the same five buildings were simulated using standardised input according to the national methodology and weather data from TRY. The results are presented in chapter 3.3.

To analyse the effect of shading balconies on indoor temperatures, daylighting and insolation in dwellings, two apartments from one case study building were modelled and analysed. The description of the building is given in chapter 2.4.3. Two different façade options regarding window and balcony layouts were studied. Results consisting of simulated indoor temperatures, temperature excess, insolation duration and daylighting – illustrating the impact of balconies – are presented in chapter 3.5.

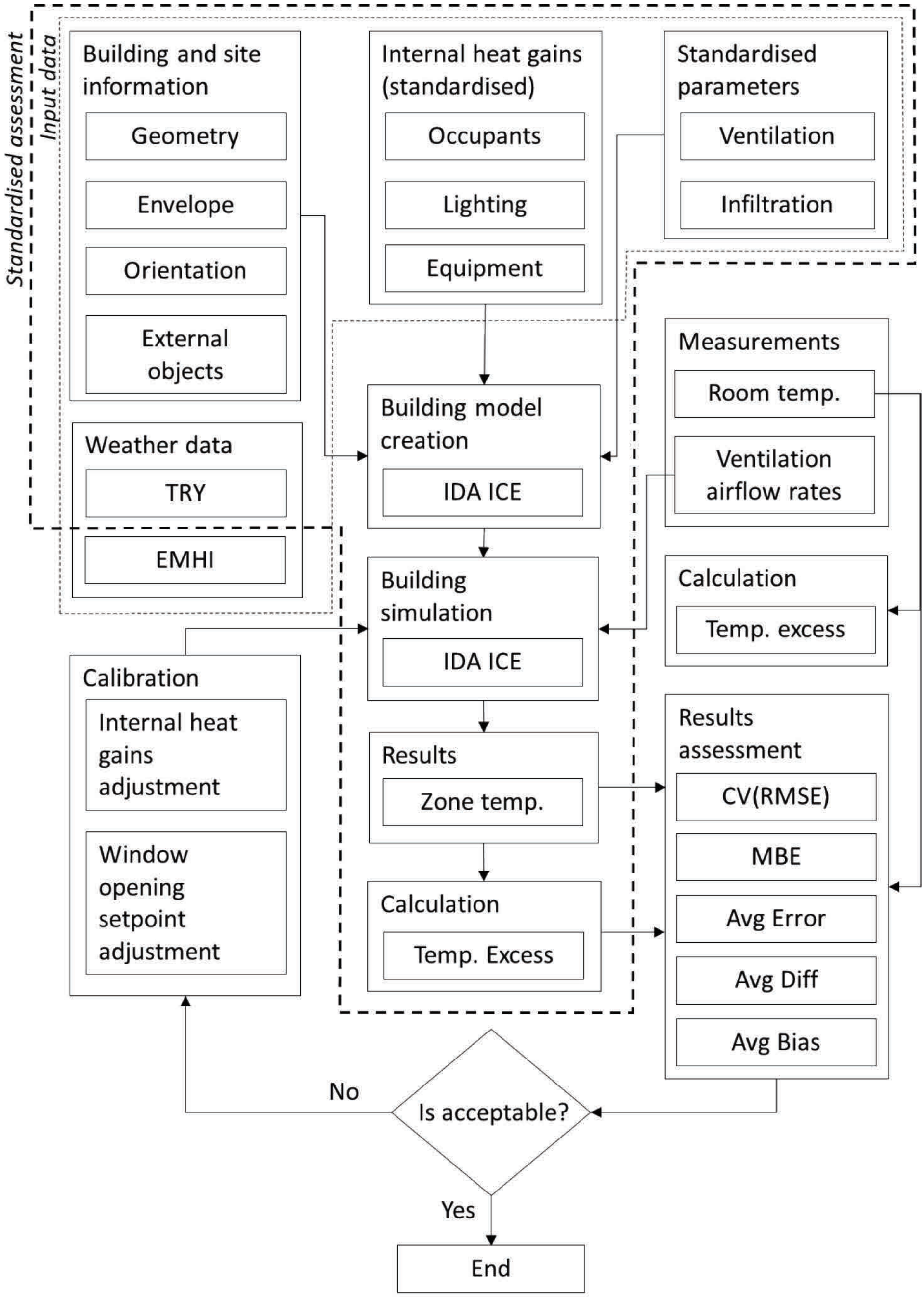


Figure 1. Flow chart of overheating assessment by standardized national methodology (showed with dashed line) and thermal zoning calibration process.

The last step was to assess and find solutions for classroom designs which ensure sufficient daylighting and low overheating risk. The overheating risk assessment procedure is similar to the assessment for residential buildings, with differences in the modelling input parameters, e.g. ventilation airflow rates, internal heat gains and profiles, and calculation parameters, e.g. allowed temperature excess limit and simulation time period. As the school building stock in Estonia is mostly constructed several decades ago and many are set to undergo renovation, as well as new school buildings are still planned, it was not possible to study already constructed new or renovated buildings. Considering the latter constraint, typical classroom façade designs are analysed based on estimations using parametric modelling and simulations. The parametric classroom model is defined and described in chapter 2.6.6. In contrast to dwellings, the simulated classroom temperature results are analysed by indoor climate class criteria and overheating risk as required by the national regulations for non-residential buildings. The analysis results are presented in chapter 3.6.

2.1 Overheating risk and thermal comfort assessment

Based on the European Union Directive 2010/31/EU [1], the Estonian Government established requirements for overheating prevention for all new buildings in Estonia. The mandatory summer thermal comfort compliance verification in Estonia, for planned buildings, is carried out according to the requirements described in Estonian Regulations No. 58, "Minimum Requirements of Energy Performance" [122] and no. 68, "Methodology for Calculating the Energy Performance of Buildings" [122] using dynamic computer simulations. The methodology states that overheating risk assessment is required for 'critical rooms', that is, rooms which have the highest potential to encounter high temperatures. In case of residential buildings, living rooms and bedrooms are analysed. When assessing compliance of a building, every single living room and bedroom is required to comply. If the requirement is not met even in one of the rooms, the whole building is considered as non-compliant and measures to prevent over the limit temperature excess have to be applied.

According to the methodology, to quantify the overheating risk, indoor temperature excess (DH) in degree-hours (Kh) is used, which is calculated from simulated or measured hourly mean room temperature values as

$$\mathrm{DH}_{t_b} = \sum_{i=1}^{j}(t_i - t_b)^+ \quad (1)$$

Where DH_{tb} is the temperature excess in degree-hours over the base temperature t_b (°C), t_i is the hourly mean room temperature and j is the total number of hours during the given period. The '+' sign means that only positive values are summed.

For residential buildings, the requirement is defined as hourly mean indoor temperature excess maximum limit of 150 Kh over a base temperature of t_b = +27°C during the summertime period from June 1 to 31 August, thus j = 2208. The equation (1) can be given as [122]

$$\mathrm{DH}_{+27°C} = \sum_{i=1}^{2208}(t_i - 27)^+ \quad (2)$$

The calculations include occupied hours only, which for residential buildings is the full period, including night-time. The allowed cumulative temperature excess in case of classrooms is 100Kh and the base temperature 25°C. The simulation periods for school buildings are set from 1st of May to the 15th of June and 15th of August to 30th of September. In this case, the total planned occupancy hours j = 782 and temperature excess can be calculated as follows

$$\mathrm{DH}_{+25°C} = \sum_{i=1}^{782}(t_i - 25)^+ \quad (3)$$

For the compliance assessment, a detailed procedure and requirements for calculation software are described in regulation No. 63 'Methodology for calculating the energy performance of buildings' [122]. The temperature excess methodology aims to express the severity of overheating and thus allows better insight into the possible problem than other static assessment methods and indices [8]. For residential buildings, the indoor temperature simulations are needed for typical living rooms and bedrooms in the building that could experience overheating. The verification is to be conducted considering rooms as single-zones and by using dynamic simulation software that meets the requirements described in [121]. One of the most important differences between modelling residential and non-residential buildings is the use of ventilative cooling through the opening of windows, which is not taken into account in non-residential buildings. In residential buildings, the opening of windows to the airing position – instead of fully opened window – is especially stressed in the regulation and the air change driven by the difference between outdoor and indoor temperature is taken into account – wind-driven air change may not be simulated, to enable the use of a wider list of simulation software and to avoid large differences in calculation results [122].

Aside from the overheating intensity assessment, for classrooms we calculated the cumulative hours for the cooling period during which the room temperature was in bounds of specific thermal environment class according to the standard EVS-EN 15251 'Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics' [9]. The hourly mean air temperature ranges for summer thermal comfort for assessing classrooms without mechanical cooling are expressed in classes are given in Table 1. The sedentary activity level of the occupants is set as 1.2met and clothing insulation level 0.6clo.

Table 1. Description of categories and temperature ranges for summer thermal comfort assessment in classrooms.

Description	Category	Temperature range, °C
High level of expectation (recommended for spaces occupied by e.g. sensitive persons, young children)	I	23.0 – 25.5
Normal level of expectation (used for new buildings and renovations	II	23.0 – 26.0
Acceptable level of expectation (should be used for existing buildings	III	22.5 – 27.0
Values outside the criteria for the above categories (should be accepted only for a limited part of the year)	IV	-

2.2 Daylighting and insolation analysis

2.2.1 Insolation requirements

The general dwelling requirements in Estonia stipulate that each living room, bedroom and kitchen must have at least one openable window, which provides an opportunity for airing and provides adequate natural lighting [124]. The specification of the natural light requirement is given in the standard EVS 894:2008/A2:2015 'Daylight in dwellings and offices' [66], which is a modified translation of the British standard BS 8206-2:2008 'Lighting for buildings. Code of practice for daylighting' [125]. The standard describes best design practice and sets out the criteria for which the requirements for adequate light can be considered fulfilled. According to the Estonian standard, all new residential buildings must be designed so that in dwellings with three or fewer rooms at least in one of the rooms continuous direct sunlight must be available minimum 2.5 hours a day throughout the period from 22 April to 22 August. In case the existing surrounding environment does not permit the fulfilment of the latter requirement, a total minimum of 3h insolation is allowed during a day (Table 2).

In planning and designing new buildings close to existing buildings, the dwellings in nearby buildings should receive sufficient insolation after the new building is constructed. The reduction of insolation duration due to the shading of the constructed new building in existing dwellings should not exceed 50% of the initial total insolation duration [66]. If the insolation of the existing dwelling affected by the designed building is found insufficient, insolation duration is not allowed to be decreased below the existing value. Orientation and window parameters of the designed dwellings should ensure sufficient insolation duration.

Table 2. Insolation requirements for residential buildings [66].

No. of rooms in dwelling	Continuous insolation duration, h	Total insolation duration, h	Min. total insolation duration, h	
			Continuous	Intermittent
1	2.5	3.0	2.5	3.0
2 to 3	2.5 in one room 2.0 in two rooms	3.0 in one room	2.5/4.0	3.0
4 and more	2.5 in two rooms 2.0 in three rooms	3.0 in two rooms	5.0/6.0	6.0

The observation point, on which the calculation is performed, is set on the outer surface plane of the exterior wall, in the middle of the window and 0.9 m above the floor of the room (Figure 2). Insolation can be considered effective if at least half of the surface of the window is in direct sunlight.

The European daylighting standard EN 17037:2019 'Daylight of buildings' [126] provides a 'minimum' of 1.5h, 'medium' 3h and 'high' >4h insolation duration periods. The main difference between the EVS 894 and the proposed EN 17037 is that the EVS 894 introduces the insolation requirement for a period during the year and EN 17037 sets a design date. The calculations are to be made on spring equinox, 21 March and compared to EVS 894, the observation point is set on the inner surface plane of the wall, in the middle of the window and at least 1.2 m above the room floor.

The reference point location for sunlight duration evaluation according to the daylight standards is presented as an example in Figure 2. Access to sunlight is determined if the reference point is insolated within boundaries of the acceptance angle α_a. The acceptance angle is limited in the morning and afternoon by the azimuths of minimum solar altitudes $\gamma_{s,\,min}$. The sunlight duration is allowed to be calculated by any reliable method that assumes the cloudless conditions and correct room orientation. Influence of various shapes of window linings and building exterior constructions need to be taken into account.

In case of window overhangs or balconies, to estimate the 'critical' depth of the overhang which would cast a shade on the reference point for insolation calculation ($\gamma_{s,max}$ = 54.1° for Tallinn) according to the Estonian standard [66], the following equation can be used:

$$L_r = \frac{x-0.9}{\tan\gamma s,max} \tag{4}$$

and in case of the European standard [126]:

$$L_r = \frac{x-1.2}{\tan\gamma s,max} - d, \tag{5}$$

where L_r is the 'critical' depth of the overhang (m), x is the overhang height from the floor (m), d is the external wall thickness (m) and $\gamma_{s,max}$ is the maximal solar altitude (Figure 2).

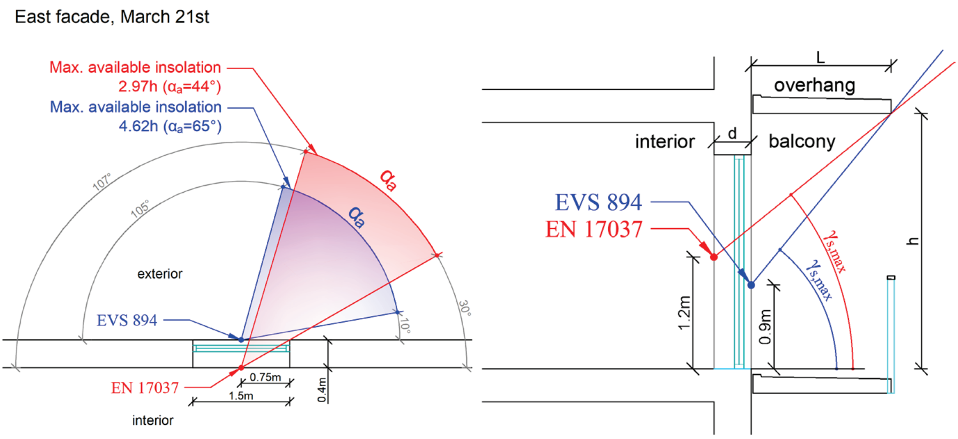


Figure 2. Sunlight availability assessment according to standards EN-17037:2019 [126] and EVS 894:2008/A2:2015 [66]: position of the observation point in plan (left) and in section (right) and its effect on insolation duration. The plan (left) shows the available solar insolation duration for an east oriented 1.5m wide window for design day, 21 March. The section (right) shows the maximum possible solar altitude in case of a balcony overhang.

2.2.2 Daylighting requirements

Daylight standards give the following methods to assess minimum daylight provision to the interior [126]:

1) Calculation of daylight factors on the reference plane.
2) Calculation of indoor illuminances on the reference plane on a short time step (0.5 or 1 hour) using validated software and climatic data for the building site.

The European standard proposes values of target illuminances and minimum target illuminances to exceed 50% of daylight hours. The method will allow confirming that the target illuminances and the minimum target illuminances are exceeded at least 50% of the time during the daylight hours. The calculation should take into account sky luminance for each time step, and handle light reflections on the external surroundings, window materials and components, internal reflections on indoor surfaces, and if appropriate or known, absorption by indoor furniture.

The mean daylight intensity factor (mDF) is used to characterize light intensity from the sky. It is a good practice to ensure that residential buildings and most other buildings are predominantly illuminated with daylight. To achieve this, mDF should be at least 2% [66]. For dwellings, the minimum mDF values are given in Table 3.

Table 3. Minimum values for the mean daylight factor (mDF) [66].

Room	Minimum mDF, %
Bedroom	1.0
Living room	1.5
Kitchen	2.0

2.3 Climatic conditions and sunlight availability

The study concentrates on buildings in Estonia, located roughly between latitudes 60º and 57º on northern hemisphere; with the capital, Tallinn, at 59.4ºN. Estonia lies in the northern part of the temperate climate zone. The climate is categorised as mild temperate, transitioning between maritime and continental, with warm, dry summers. The average annual temperature is +5.2°C and average temperatures during the warmest month (July) range from +16.3°C on the Baltic islands to +18.1°C inland in July [123]. The probability that daily maximum temperatures exceed +30°C is highest in July. In the inland regions of Estonia, such temperatures occur nearly every year and in coastal areas every third year [127]. Climate change scenarios for Estonia estimate an increase in the annual mean temperature of 3-4 K [128] and around 5 days annually with temperatures above +30°C [129] for the end of the 21st century, showing a high probability of heatwaves.

When assessing building performance regarding both energy consumption and summer thermal comfort assessment calculations, according to the ordinance No. 68 [122], the simulations are required to perform regardless of the location of the building using the TRY [130]. The TRY is constructed from selected weather data from different months of 31 years (1970-2000) and represents a typical climate for the Estonian region. It contains hourly mean data of outdoor temperature, relative humidity, wind speeds and solar radiation. Hourly temperatures and global irradiation for every month from TRY are presented in Figure 3 to illustrate the climatic conditions. The climate throughout the land is fairly uniform, although slightly milder in the coastal areas. Spring and autumn days can be as hot as in midsummer, as sunny weather and warm air masses arriving from the south-east can drastically increase the temperature.

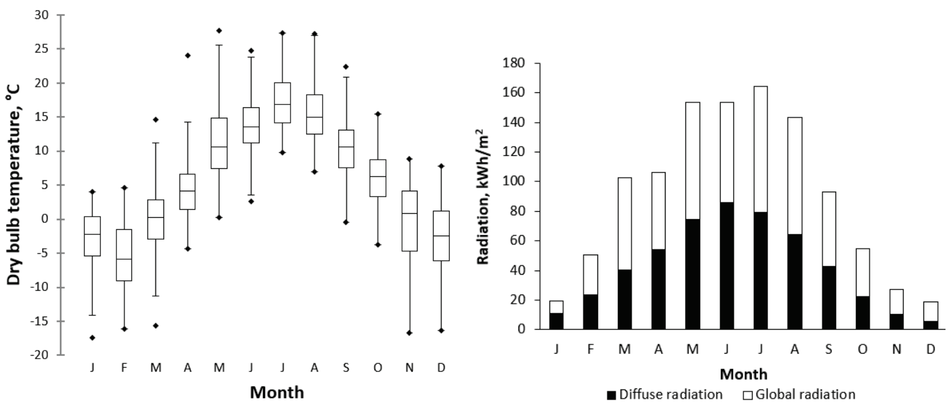


Figure 3. Hourly outdoor temperature distribution (left) and monthly solar radiation (right) in Estonia (data from TRY [130]).

The indoor temperature measurements in dwellings were performed in the summer of 2014. Compared to outdoor temperatures from TRY a typical summer of 2013 (Figure 4, left), the 2014 summer was relatively warm, with two distinctive heat waves with hourly mean outdoor temperatures reaching higher than +30°C (Figure 4, right). The outdoor temperature excess $DH_{+27°C}$ in 2013 was 24.3 Kh and in 2014 157.3Kh, whereas in case of TRY the temperature excess $DH_{+27°C}$ is 0.5Kh (Figure 4, left). For the measurement year, 2014, a custom climate file was created using the measured data from a nearby weather station.

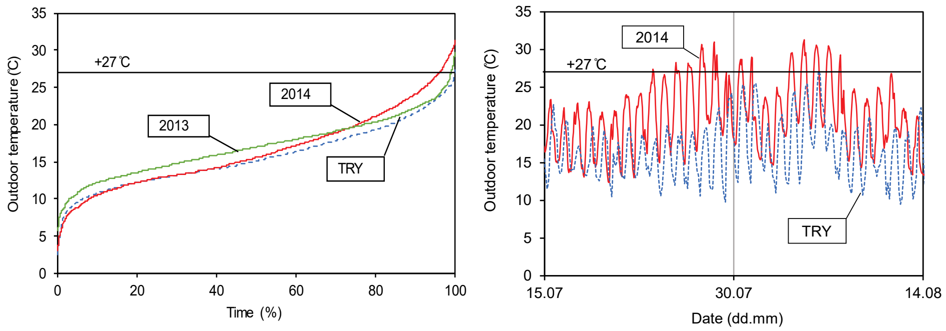


Figure 4. Hourly mean outdoor temperature duration curves for summertime period from July 1st to August 31st (left) and heatwaves in June and August 2014 (right). Data from TRY [130] and weather station measurements (Estonian Weather Service, EMHI [123]) in years 2013 and 2014.

Potential available sunlight during months, days and hours can be estimated from the sun path diagram for latitude 59ºN shown in Figure 5. Depending on the daytime duration and sky clearness, the sunshine duration during summer months is roughly ten times longer than in winter months [131]. Aside from Estonia, the same latitude region on which the results of the study can be applied, covers amongst others, parts of Sweden (e.g. Stockholm), Norway (e.g. Oslo), Finland (e.g. Helsinki), Russia (e.g. St. Petersburg), USA (e.g. Juneau, Alaska), etc.

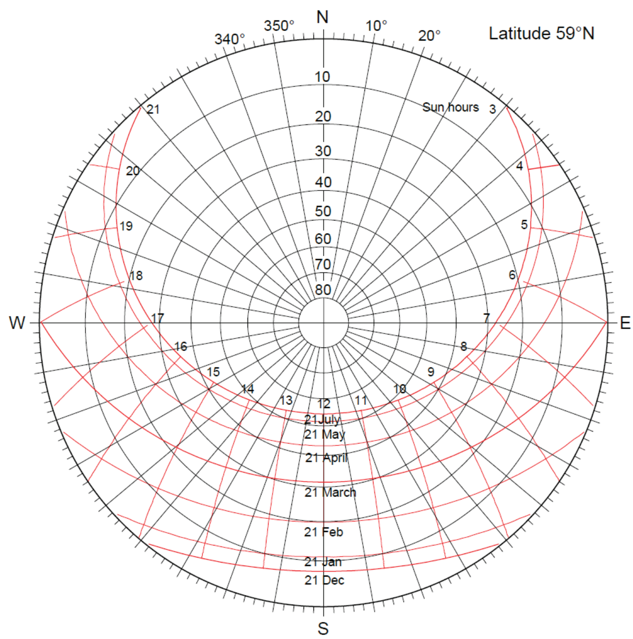


Figure 5. Sun path diagram for latitude 59°N (Tallinn, Estonia).

2.4 Analysed buildings

2.4.1 Description of the selected residential buildings

The apartment buildings pertaining to this study were selected randomly, using the criterion of the building's permit acquisition year 2009 and later, to define each building as “new”, based on the regulations’ entry into operation. The buildings varied in terms of architectural design, envelope construction type, number of glazed surfaces and window types, geometry, height, location, orientation and other factors. Most of the buildings were designed with precast or monolithic concrete structures with more than four floors above ground. Table 4 gives an overview of the main building parameters used as input data for simulations. The data were acquired from the buildings design documentation and Energy Performance Certificates (EPCs). An example of a typical apartment architectural plan and buildings cross-section is shown in Figure 6. The thermal transmittances for the envelope parts as presented in Table 4 were calculated in the simulation software by defining the material layers defined also in the design documentation. The room sizes in apartments varied in large numbers – the average floor area of living rooms was 28.9 m^2 with a standard deviation of 10.4 m^2, for bedrooms the average floor area was 12.5 m^2 and a standard deviation of 3.3 m^2.

The buildings in this study used either a central mechanical exhaust ventilation system or a decentralized mechanical supply-exhaust system with apartment-based air handling units – both commonly used in Estonian residential buildings. In case of the mechanical exhaust systems, outdoor air was supplied to the dwellings through fresh air valves, located in external walls, or through window integrated air valves.

As of passive cooling techniques, besides ventilative cooling, only one building had glazing with a low g-value (0.4) for south–west-oriented façade; one of the studied apartments had internal venetian blinds between the windowpanes, and most commonly, the use of balconies as shading elements were identified. Other intentional measures, such as external window shading, were not registered. Also, no active cooling measures in the buildings were registered – a common practice in Estonian apartment buildings.

The thermal transmittances of the buildings' envelope were found to be between 0.15 and 0.25 W m^{-2} K^{-1} for external walls, 0.09 and 0.17 W m^{-2} K^{-1} for roofs, and 0.60 and 1.65 W m^{-2} K^{-1} for windows, with solar factors varying from 0.40 to 0.71.

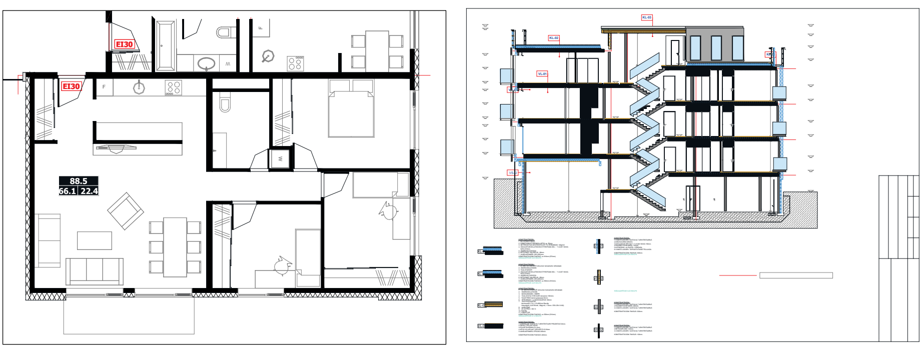


Figure 6. Example of a studied buildings architectural drawings: apartment plan (left) and building cross-section with specifications of the building structures (right).

Table 4. Specification and input data used in simulations (data collected from building design documentation and EPCs).

Building No	Building structure type	Thermal transmittance of envelope part, W m^{-2} K^{-1}			Windows g-value, -	Ventilation system type	Building height, m	Floors above ground	Infiltration, $l \cdot s^{-1} \cdot m^{-2}$ ext. surf.	Passive cooling elements
		Ext. wall	Roof	Windows						
B1	Wood-frame	0.21	0.16	1.06	0.68	Mech. exhaust	10.6	4	0.042	balconies
B2	Wood-frame	0.17	0.14	0.63	0.55	Mech. supply-exhaust	11.0	4	0.042	-
B3	L/W concrete blocks	0.16	0.14	1.10	0.69	Mech. exhaust	12.0	4	0.042	-
B4	Concrete	0.15	0.17	1.14	0.71	Mech. exhaust	26.5	10	0.056	-
B5	L/W concrete blocks	0.18	0.12	1.10	0.65	Mech. supply-exhaust	19.3	6	0.056	balconies
B6	Concrete	0.24	0.14	1.00	0.40	Mech. supply-exhaust	18.5	6	0.056	balconies
B7	Precast concrete	0.23	0.12	1.01	0.55	Mech. exhaust	14.6	5	0.056	balconies / shading trees
B8	Precast concrete	0.17	0.09	0.60	0.48	Mech. exhaust	21.0	6	0.056	balconies
B9	Precast concrete	0.17	0.14	0.89	0.60	Mech. exhaust	14.0	4	0.042	balconies
B10	Precast concrete	0.23	0.16	1.20	0.63	Mech. supply-exhaust	24.9	7	0.056	cross ventilation
B11	Concrete	0.16	0.14	1.10	0.69	Mech. exhaust	21.5	6	0.056	-
B12	Concrete	0.22	0.15	1.00	0.70	Mech. supply-exhaust	17.0	5	0.056	-
B13	Precast concrete	0.23	0.16	1.10	0.67	Mech. supply-exhaust	25.1	7	0.056	-
B14	Wood-frame	0.25	0.17	1.40	0.70	Mech. exhaust	8.3	2	0.035	shading trees / cross ventilation
B15	Precast concrete	0.21	0.12	1.65	0.63	Mech. supply-exhaust	12.0	3	0.042	balconies
B16	Precast concrete	0.21	0.12	1.65	0.63	Mech. supply-exhaust	12.0	3	0.042	balconies
B17	Concrete	0.23	0.13	1.01	0.55	Mech. exhaust	16.0	5	0.056	-
B18	Precast concrete	0.18	0.11	1.30	0.63	Mech. supply-exhaust	10.9	3	0.042	balconies
B19	Precast concrete	0.18	0.11	1.30	0.63	Mech. supply-exhaust	13.9	4	0.042	balconies / cross ventilation
B20	Precast concrete	0.19	0.09	0.80	0.50	Mech. supply-exhaust	24.7	9	0.056	balconies / cross ventilation
B21	H/W concrete blocks	0.18	0.14	0.92	0.54	Mech. supply-exhaust	7.2	2	0.035	cross ventilation
B22	L/W concrete blocks	0.16	0.13	1.10	0.60	Mech. supply-exhaust	7.0	2	0.035	shading trees / balconies
B23	Precast concrete	0.17	0.14	1.00	0.55	Mech. exhaust	10.3	3	0.042	balconies / cross ventilation
B24	Precast concrete	0.18	0.11	1.10	0.58	Mech. supply-exhaust	21.2	6	0.056	balconies
B25	L/W concrete blocks	0.16	0.12	1.04	0.56	Mech. exhaust	8.7	2	0.035	balconies

2.4.2 Description of the apartment buildings chosen for detailed analysis

Five apartments from five different buildings were studied, modelled and simulated. The relevant information for building structures, dimensions, building site and other parameters was acquired from buildings' design documentation. Overview of the specifications of external boundaries, windows and other parameters of the buildings is given in Table 5. The studied buildings were constructed between 2011 and 2014. From each building, one apartment was selected for the analysis. Example plans and analysed rooms of the apartments are shown in Figure 7. All the buildings had apartment-based mechanical supply and exhaust ventilation units installed. Outdoor air was supplied to living rooms and bedrooms and removed from bathrooms and kitchens. The air handling units were equipped with summer bypass function for the heat exchanger. During the summer period, no heating systems were utilized in the buildings. Also, no mechanical cooling systems were installed (Figure 8).

Table 5. Specifications overview of the studied buildings.

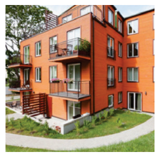
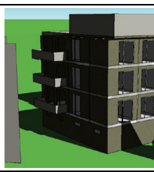
Building no	B1	B2	B3	B4	B5
Photo of the studied Building					
3D view of the building model in IDA ICE					
Construction year	2014	2012	2011	2012	2013
Envelope construction	Concrete	Concrete	Pre-cast concrete	Pre-cast concrete	Concrete block
Building height (m)	14.0	11.7	21.0	12.0	10.6
Floors above ground	4	4	6	3	3
Apartments	12	21	40	14	9
Net heated area (m^2)	1 137	1 580	3 114	891	742
Volume (m^3)	5 465	6 043	11 422	4 872	2 884
Ext. wall U-value ($W/(m^2{\cdot}K)$)	0.20	0.16	0.17	0.21	0.19
Roof U-value ($W/(m^2{\cdot}K)$)	0.12	0.14	0.09	0.12	0.13
Windows U-value ($W/(m^2{\cdot}K)$)	1.10	1.00	0.89	1.10	1.20
Windows g-value	0.65	0.45	0.60	0.63	0.67

Figure 7. Example of apartment plans and analysed rooms (highlighted) of the studied buildings: bedroom, B1 (a); bedroom, B2 (b) bedroom, B4 (c), living room B3 (d) and living room, B5 (e).

Figure 8. Photos from the studied rooms: (from left) bedroom, building B1; bedroom, building B2; living room, building B3; living room, building B4 and bedroom, building B5.

2.4.3 Case study building for estimating the effect of shading balconies

The case study building for studying the effect of balconies was a seven-floor height concrete structured apartment building built in 2016 in Tallinn (Figure 9). The specification of the building envelope elements and parameters are gathered from the architectural design documentation. External walls are from reinforced concrete sandwich panels, with 200 mm mineral wool insulation in between the panels. The thermal transmittance of the walls is 0.17 W/(m^2·K). The height of the floors is 3m and room height of the apartments is 2.645m. The initial balconies were designed with a depth of 1.5m. The building envelope elements parameters are given in Table 6. The studied apartments were located on the 6th floor.

Figure 9. Rendered image (left) (view from the east) and typical floor layout (right) of the studied building.

Table 6. Envelope parameters of the case-study building.

Parameter	Value	Unit
Building height	22.2	m
No. of floors total / (floors with apartments)	7 / (6)	-
Air permeability q_{50}	3.0	$m^3/(h{\cdot}m^2$ of ext. surf.)
Thermal transmittance:		
- External walls	0.17	$W/(m^2{\cdot}K)$
- Roof	0.12	$W/(m^2{\cdot}K)$
- Windows	1.1	$W/(m^2{\cdot}K)$
- Window frame	2.0	$W/(m^2{\cdot}K)$
Solar factor of windows (g-value)	0.4	-

2.5 On-site measurements

Indoor temperature measurements were carried out during the period from 1 July to 31 August in 22 apartments in 16 of the studied apartment buildings in either living rooms or bedrooms in the selected apartments. The chosen apartments in each building were assumed to have the highest risk of overheating, for example, with south or west orientation, on higher floors, large glazing areas etc (Figure 10). For measurements, calibrated data logging Onset Hobo U12-012 devices [132] were used. The temperature measuring range of the devices is from -20 to +70°C, with accuracy ±0.35K, and relative humidity from 5% to 95%, with accuracy ±2.5% of full-scale output. The data loggers were placed in the occupied zone of the rooms so that they would not be affected by direct sunlight, ventilation airflows, heat-generating equipment and so on. The placement height of the loggers was between 1.0 and 1.6m. For every measurement taken, correction factors according to calibration results were applied. Ventilation air flows from supply and exhaust valves and grilles were measured with SwemaFlow 234 airflow hood with a range of 2–65 l/s and uncertainty ±2.5% of the reading value.

The weather data measurements were acquired from nearby weather station. The data consisted of hourly outdoor temperatures, direct and diffuse solar radiation, relative humidity, wind speed and direction.

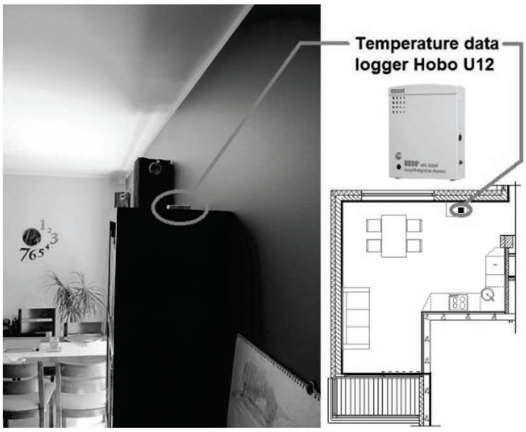


Figure 10. Example placement of a temperature data logger Hobo U12 used in room temperature measurements, photo of the studied dwelling (left) and room plan (right).

2.6 Thermal modelling and simulations

To estimate indoor temperatures to determine overheating risk and for assessing the apartment buildings compliance with summer thermal comfort, room temperature simulations are required [121]. For the purpose, we used indoor climate and energy simulation software IDA Indoor Climate and Energy (ICE) [133]. This tool allows detailed and dynamic whole-year multi-zone building simulations of indoor climate, energy consumption and building systems performance. The software has been validated according to the European Standard EN-ISO 13791 'Thermal Performance of Buildings - Calculation of Internal Temperatures of a Room in summer without Mechanical Cooling - General Criteria and Validation Procedures' defined test cases [134], to Envelope BESTEST in IEA Task 12 [135] and used in several similar studies [136-139].

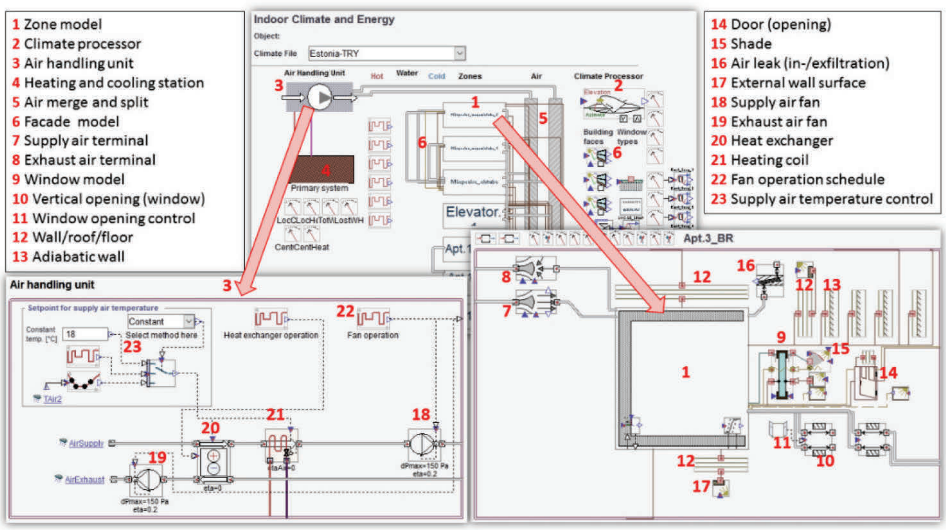


Figure 11. Schematic view of the IDA ICE environment: example of a whole building model fragment.

An example schematic view of the whole building model in IDA ICE simulation environment (SE) is presented in Figure 11. The IDA ICE SE is a general-purpose modelling and simulation tool for modular systems where components are described with mathematical equations, written in the Neutral Model Format. More detailed information, for the component modules and IDA solver, can be obtained from several publications [140-143].

2.6.1 Thermal modelling input data

Input data for the buildings in question, including building site surroundings, architecture, floor plans, and specifications for walls, roofs and windows were acquired from the design documentation of the buildings, the Estonian Registry of Buildings database [144] and the Estonian Land Board web map [145].

Each material layer included properties for specific heat and density for accurate calculation of building thermal mass. Solar heat gain coefficients of windows, if not available in design documentation, were calculated using detailed window model with glazing properties calculation tool in IDA ICE. Overall values used in buildings simulations are shown in Table 5.

Trees close to the buildings that would cast shadows were modelled as crossing vertical rectangular planes (Figure 12). The shading effect of foliage was estimated as a transparency factor between 0.2 and 0.3 (with 1.0 being fully transparent) [146].

The simulations were made according to the methodology described in [122]. The simulation models for temperature-based overheating assessment as required by the national regulation use a single-zone method, meaning that only selected rooms are modelled individually with no connections to other rooms (Figure 12). In case of residential buildings, at least two 'critical' rooms are required to simulate, one bedroom and one living room, which have the biggest potential to score high temperatures, for example, south or west orientation, higher floor location, and large glazed surfaces. The selection of these rooms is up to the energy efficiency specialist, designer or HVAC engineer responsible for the calculations (Figure 12).

The thermal properties of external boundaries were calculated automatically in IDA ICE by defining the material layers with specific parameters values for each layer, which included properties for thermal conductivity, specific heat and density for accurate calculation thermal mass of the building and heat fluxes through the structures. The overview of the material propertied used is given in Table 7.

Figure 12. Example of modelled buildings with shading elements and selection of 'critical' rooms, which have highest potential to become overheated. Photos (top) and simulation models (bottom).

Solar heat gain coefficients of windows, if not available in design documentation, were calculated using detailed window model with glazing properties calculation tool in IDA ICE. Overall values used in buildings simulations are shown Table 4.

Table 7. Overview of the material properties used in the thermal transmittance calculations of building envelope structures.

Material	Thermal conductivity, W m^{-1} K^{-1}	Specific heat capacity, J kg^{-1} K^{-1}	Density, kg m^{-3}
Concrete	2.00	1000	2400
Gypsum board	0.25	1000	900
Mineral wool	0.04	850	60
Oriented strand board (OSB)	0.10	1880	555
Wood	0.14	2300	500
Expanded polystyrene (EPS)	0.04	850	15
Concrete block	1.19	880	2100

Infiltration for the buildings was calculated using the following equation [122]:

$$q_i = q_{50} \times A/(3.6 \times z) \quad (6)$$

Where q_{50} is the building air permeability at 50 Pa pressure difference, $m^3 \cdot h^{-1} \cdot m^{-2}$; A is the total area of building envelope, m^2 and z is the building height factor: 35 for one, 24 for two, 20 for three and four and 15 for five and higher story buildings. For all of the cases, building air permeability value of 3.0 m^3 h^{-1} m^{-2} was used, as is required for calculations in case of new buildings, according to [122].

The opening and closing of windows were modelled using an on/off temperature control macro with a deadband of 2K (Figure 13). This means that windows would open when room temperatures rose 1K above the set-point temperature value, and close when dropped 1K under the set-point value.

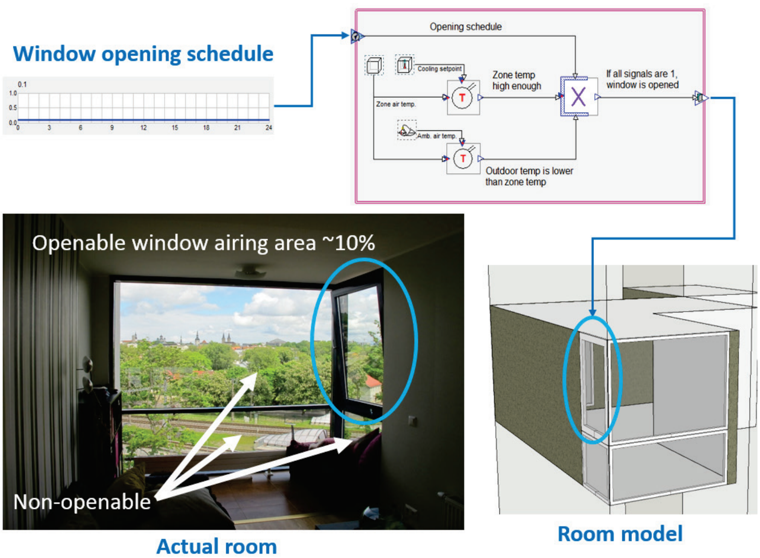


Figure 13. Window opening control macro used in the simulations in IDA ICE: the window is opened, when the zone temperature exceeds cooling set-point t_{cool} + Δt/2, and the outdoor temperature is lower than the room temperature; window is closed when the zone temperature drops below t_{cool} – Δt/2. Δt is defined as deadband value.

When the outdoor temperature exceeded indoor temperature values, the windows would also close (Figure 13). As the set point for opening and closing windows is not defined in the regulations, the lowest possible value for deadband 2K was used, that is, +22°C ±1K, which would not conflict with the heating setpoint +21°C. With this setting, the windows would be opened at +23°C, and closed at room temperatures below +21°C, ensuring accordance with the methodology [121]. The openable area of the windows was calculated as a percentage of the openable window total area, depending on the height and width of the window, imitating the airing position.

Internal heat gains for dwellings were used according to regulation No. 63 [122]: 28.3 m^2 floor area per occupant with heat emission of 125W, including 85W sensible heat, the maximum load for equipment 3 and lighting 8 W m^{-2}. Daily occupancy and load profiles were applied to the models as shown in Figure 14.

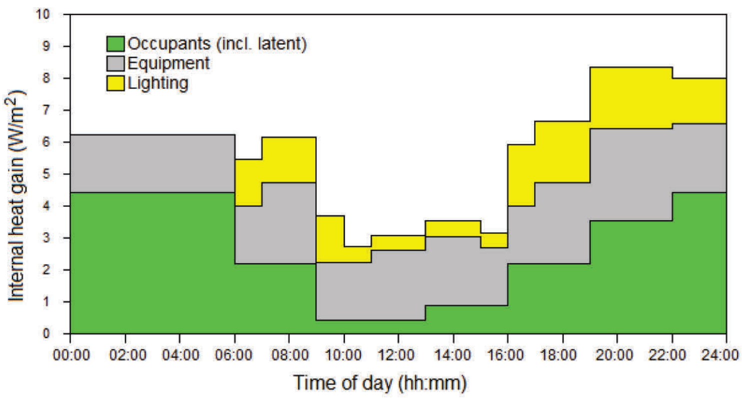


Figure 14. Internal heat gain profiles for lighting, equipment and occupancy in apartment buildings according to Estonian regulation No. 63 [122].

Ventilation in dwellings was modelled as well mixed with a constant supply and exhaust airflow rate of 0.5 l s^{-1} m^{-2} [121]. In apartments with central mechanical exhaust ventilation, the supply air temperature was taken to be equal to the outdoor temperature. For apartments with local air-handling units (AHUs), the rise in the supply air temperature of 1K was accounted, because of the supply fan heat emission. Considering the bypass option of domestic AHUs, the heat exchanger effect was not modelled.

2.6.2 Quantifying the effect of thermal zoning

To quantify the effect of thermal zoning on the simulated indoor temperature results and to determine the suitability of temperature-based simulations for assessing overheating, five apartment building models were analysed. The buildings used in the detailed analysis are described in chapter 2.4.2.

We used three different thermal zoning approaches for building modelling (Figure 15):

- multi-zone approach, with all the rooms in the building modelled;
- multi-zone approach, with only rooms in the apartment modelled;
- single-zone approach, with only the analysed room modelled.

In case of the apartment-based method, thermal connections and air leakages between other rooms and neighbouring apartments, openings and boundaries were not accounted – heat and air transfer were modelled only between the rooms in the apartment and outdoor environment, for example, external walls, internal walls and windows.

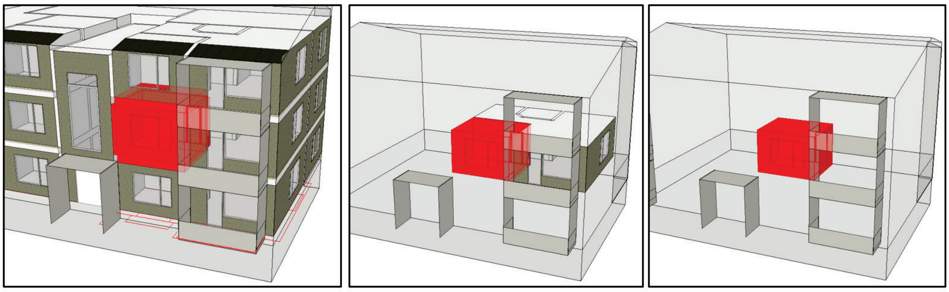


Figure 15. Simulation model detail for different calculation methods: whole building model (left), apartment without neighbouring zones (middle) and single room model (right).

The single-zone method accounted only for connections with external walls and windows, and the neighbouring sides of internal constructions were modelled as adiabatic. The multi-zone method, however, accounted for connections between all the rooms in the apartment. In the single-zone method, both supply and exhaust ventilation were modelled as room-based.

First, whole building models were created and simulated with IDA ICE, using weather data from a local weather station for the year 2014, acquired from the Estonian Weather Service [123]. The detailed building models were calibrated to acceptable agreement with the indoor temperature measurements from a one-month measuring period by changing internal gains, temperature setpoints for window opening control and by adding internal drapes to the window models. The models were adjusted until acceptable margin of error and correlation with measurements was achieved by evaluating the metrics described in chapter 2.6.3.

The five calibrated building models were then simulated using weather data from TRY to get a base value for temperature excess and evaluate the buildings' compliance with overheating requirements. To analyse the impact of thermal zoning, the two alternative simulation models – apartment and single-zone – were created by removing neighbouring zones from the original whole building model: for the first model, only the rooms in the apartment were kept and for the second model, only the analysed rooms were kept. Simulation results from the latter models were also compared with the results from the calibrated whole building model.

Based on the respective simulation results using real weather data, base temperature values for temperature excess calculations were calculated for each building to get respective excess values with measurement results.

2.6.3 Evaluation of simulation results

The correlation between the measured and simulated indoor temperature was assessed by linear regression analysis using Pearson correlation coefficient as one of the indicators.

To validate the calibrated models, we used the coefficient of variation of the root mean squared error, CV(RMSE) (7) and the mean bias error (MBE) (8) to quantify the overall accuracy of the simulations [147]:

$$CV(RMSE)(\%) = \frac{\sqrt{\sum_{i=1}^{n}(Sim_i - Meas_i)^2/n}}{\overline{Meas}} \times 100\% \qquad (7)$$

$$MBE(\%) = \frac{\sum_{i=1}^{n}(Sim_i - Meas_i)/n}{\overline{Meas}} \times 100\% \tag{8}$$

where $Meas_i$ is the measured value of the variable, Sim_i is the simulated value of the variable, $\overline{Meas}$ is the mean value of the measured variable and *n* is the number of data points. The coefficient of variation of the root mean squared error CV(RMSE) is essentially the root mean squared error divided by the measured mean of the data [148]. Comparisons were conducted in terms of predicted indoor temperatures. The CV(RMSE) of the hourly simulation results and measured data were calculated [149].
To evaluate the quality of the simulation results, additional parameters are used, such as average error percentage (9), the average difference between measured and simulated results (10) and average bias (11) for the specified period:

$$Avg.Error(\%) = \sum_{i=1}^{n} \left| \frac{Sim_i - Meas_i}{Meas_{Max} - Meas_{Min}} \right| \times \frac{100\%}{n} \tag{9}$$

$$Avg.Dif(K) = \frac{\sum_{i=1}^{n} |Sim_i - Meas_i|}{n} \tag{10}$$

$$Avg.Bias(K) = \frac{\sum_{i=1}^{n} (Sim_i - Meas_i)}{n} \tag{11}$$

2.6.4 Combined simulations for overheating and daylighting

We used IDA ICE to estimate hourly indoor temperatures, insolation duration and mean daylight factors for the case study building to analyse the impact of balconies on overheating prevention, daylight and sunlight availability. The integrated daylighting analysis in IDA ICE is based on RADIANCE engine [150, 151], allowing precise zone illuminance and daylight factor calculations.

We studied two apartments, one of which had south and east-facing façades and the other south and west oriented façades. For the analysis, we chose multiple façade layouts – different window combination and two options for balconies: full façade length (case 1) and separate for each room (case 2). The façade layouts for different windows and balcony doors were used to justify the balcony layouts. The balconies were separated with opaque floor high side-fins, 3.0m apart, and guard rails with a height of 1.0m. The simulation models are shown in (Figure 17). The studied window configuration variations are shown in Figure 16 and window parameters in Table 8. Balcony depth variations were 0.6m, 0.9m, 1.2m and 1.5m.

The National Building Code Act [152] requires for every living room, bedroom or kitchen to have at least one openable window. Thus also, the most commonly used measure to remove excess heat in dwellings is ventilative cooling through openable windows. The latter occupant behaviour was simulated by implementing a temperature controller with a setpoint of 26.5°C at which the window was opened by the extent of the openable area fraction (Table 8).

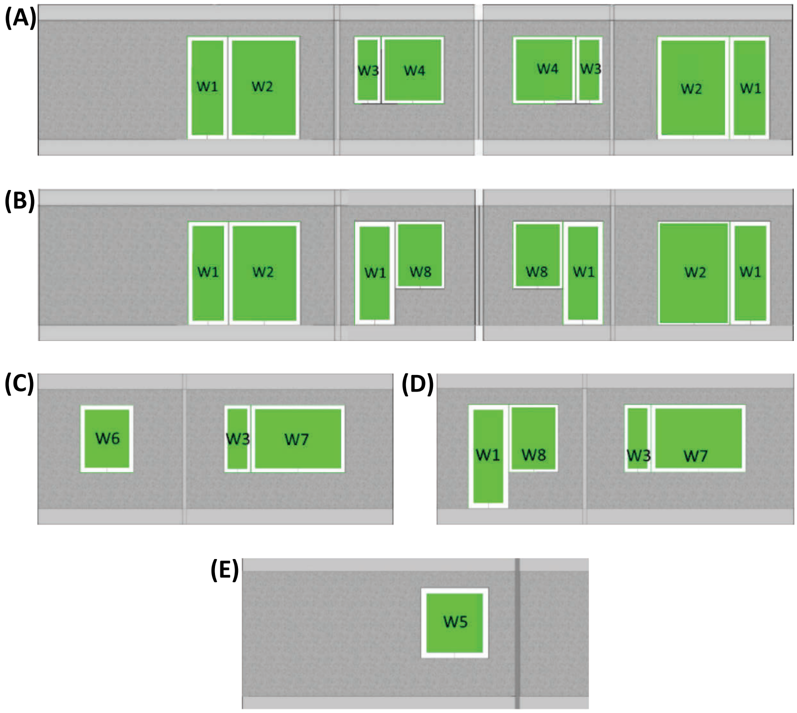


Figure 16. Window configuration cases for different façade orientations: south-oriented full façade length balconies (A), south-oriented separate balconies (B), west oriented full façade length balconies (C), west oriented separate balconies (D) and east oriented façade for both cases (E).

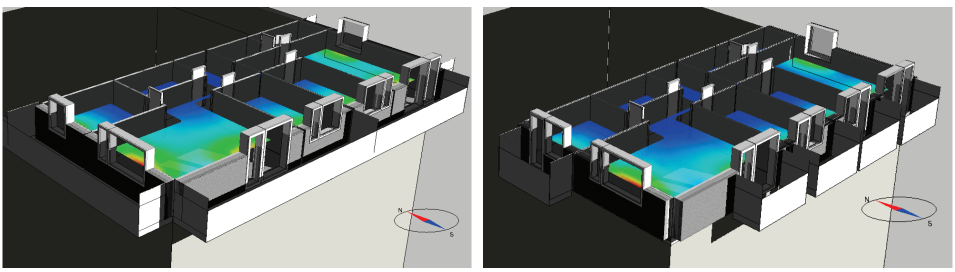


Figure 17. Studied façade configurations: full façade length: case 1 (left) and separate balconies: case 2 (right).

Table 8. Window parameters.

Code	Width x height, m	Frame fraction, %	Openable area fraction, %
W1	0.9x2.3	30	15
W2	1.6x2.3	20	-
W3	0.6x1.5	35	20
W4	1.4x1.5	20	-
W5	1.5x1.5	30	-
W6	1.2x1.5	30	-
W7	2.1x1.5	20	-
W8	1.1x1.5	20	-

Table 9. Room and window parameters for analysed cases.

	Room code*	Windows	Area, m^2				WWR,	WWR·g,	WFR,
			Floor	Windows	Glazing	Façade	-	-	-
Case 1	A1-BR1	W3+W4	12.6	3.0	2.27	7.4	0.30	0.12	0.18
	A1-LR	W1+W2; W5	28.32	8.0	5.97	26.5	0.22	0.09	0.21
	A2-BR1	W3+W4	13.25	3.0	2.27	7.9	0.29	0.11	0.17
	A2-BR2	W6	12.43	1.8	1.26	8.5	0.15	0.06	0.10
	A2-LR	W1+W2; W3+W7	41.4	9.8	7.50	29.5	0.25	0.10	0.18
Case 2	A1-BR1	W1+W4	12.6	4.2	3.13	7.4	0.42	0.17	0.25
	A1-LR	W1+W2; W5	28.32	8.0	5.97	26.5	0.22	0.09	0.21
	A2-BR1	W1+W4	13.25	4.2	3.13	7.9	0.40	0.16	0.24
	A2-BR2	W1+W8	12.43	3.7	2.77	8.5	0.33	0.13	0.22
	A2-LR	W1+W2; W3+W7	41.4	9.8	7.50	29.5	0.25	0.10	0.18

*Room code abbreviations: A - Apartment; BR - Bedroom; LR - Living Room; WWR – window to wall ratio, g – solar factor, WFR – window to floor ratio.

Aside from natural ventilation using window airing, each apartment was modelled with mechanical supply-exhaust ventilation unit with a constant airflow rate of 0.5 $l/(s·m^2)$ [121]. During the simulated summer period, ventilation unit heat exchanger was set to by-pass regime, meaning that the supply air temperature was equal to the outdoor temperature.

Maximum internal heat loads from occupants, lighting and equipment were defined in the simulation models according to the national regulation and are shown in Table 6 The heat loads were applied to every room as hourly profile based on typical dwelling usage rates (Figure 14). For the studied apartment configurations, WWR, WWR·g-value and WFR parameters are shown in Table 9.

2.7 Parametric classroom model creation

We have analysed a classroom parametric model through computer simulations to assess indoor temperatures, overheating risk and daylighting. The parameters used in the simulation model creation are shown in Table 11 and Table 12. The room model variations used in paper IV included different room widths and depths (5m, 6m, 7m, 8m and 9m) for a total of 25 room size and layout variations. The parametric model used in paper V combines all the room depths, widths and orientations based on 2 room types different for glazing Visible Transmittance (VT) and use of shading, excluding same combinations of north orientation for a total of 175 (Figure 18). The window layout was varied in accordance with the room width. For the 5m wide room, two 1.9x1.7m (width x height) windows (WWR 45.6%) were used; for the 6m wide room, three 1.466x1.7m windows (WWR 41.5%); for the 7m wide room, three 1.8x1.7m windows (WWR 43.7%); for 8m wide room, four 1.45x1.7m windows (WWR 41.1%) and for the 9m wide room, four 1.7x1.7m windows (WWR 42.8%) were used. The floor height of the room was 3m for all the variations. As a passive measure to reduce external heat gains from direct sunlight into the room, horizontal shading with a depth of 0.9m on top of the windows as an option for east, south and west orientations was used. The overhang was modelled as a single horizontal element located 10cm above the windows. Additionally, ground surface with 20% reflectance was modelled outside the room.

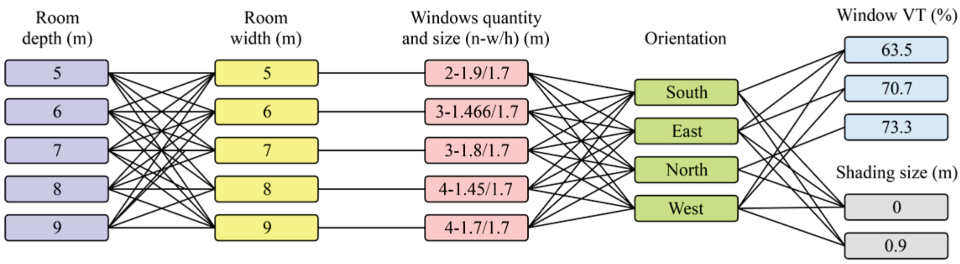


Figure 18. Diagram of room parameter combinations. Code: n - quantity of windows, w – window width; h – window height.

2.7.1 Daylight factor simulations

The parametric model of the classroom was built using the software Grasshopper for Rhinoceros [153] and the analysis was carried out with daylighting design plug-in DIVA4 (Figure 19), which performs simulations through validated software Radiance [154, 155].

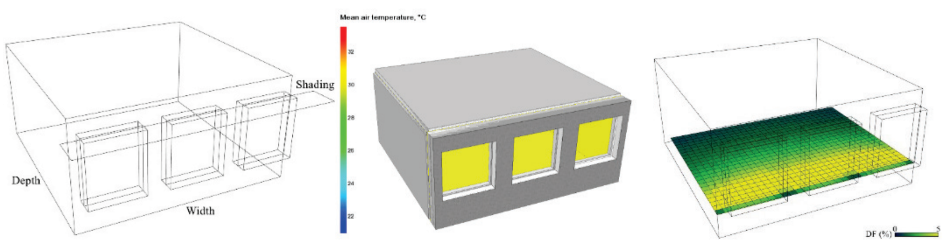


Figure 19. Classroom model used in the study (left), examples of indoor temperature calculation model in IDA ICE (middle) and daylight factor calculation model in Grasshopper using DIVA4 (right).

Through the daylight analysis parametric model it is possible to assign reflectance values to interior elements of the room (i.e. floor, wall, ceiling, external shading and ground) and visible transmittance (VT) values to the glazed surface of windows, set the simulation grid, select the simulation parameters, run the simulations and record result data. The reflectance values used in the simulations were the same for all the classroom variations and are standard values recommended for Daylight Factor calculations, presented in Table 11. VT values and shading were assigned selectively to the room combinations depending on the depth, width and orientation with the scope to obtain classrooms which fulfil the Estonian requirement for maximum DH. Windows were modelled with a frame size of 5cm except the operable window with a frame of 15cm.

Table 10. Standard/improved material reflectance values.

	Walls	Floor	Ceiling	Shading	Ground
Reflectance	50/70	20/40	70/80	35	20

For interiors, daylight assessment regulations recommend standard conservative reflectance values. In addition, in the study described in paper V, improved reflectance values are also used to get a larger number of combinations, for a total of 350, and perform simulations using real case reflectance parameters (Table 10). No surrounding buildings are modelled because of open areas locations of majority of new schools. The presented glazing VT values are used in the DF model.

The daylight parametric model permits to associate the glazing VT values in different ways and to use external shading as an option. This procedure has been necessary to match the room variation parameters used for energy efficiency studies. Different combinations of glazing VT and use of shading have been used for the different orientations in consideration of the Estonian overheating prevention requirements. Because Daylight Factor analysis does not take into account windows orientation, daylight simulation combinations refer solely to glazing VT and use of shading. The combinations are presented in Table 12.

The grid used for the simulation has a size of 0.2m, was located at 0.75m from the floor and occupies 80% of the floor area. The main Radiance parameters used in the simulations are: -aa .1 (ambient accuracy); -ab 5 (ambient bounces); -ad 1024 (ambient divisions); –ar 256 (ambient resolution). As required for DF simulation the CIE overcast sky model was used. The Daylight Factor simulations were performed automatically for all the classroom size and parameters variations through an automation function of the parametric model and the values of mDF were recorded for each iteration.

Table 11. Simulation input parameters.

Schedules		Internal heat gains			HVAC systems		Daylighting
Internal gains	Ventilation	Occupancy	Lighting / Equipment	Temp. setpoint	Supply air temperature	CAV air flow rate	Reflectance values (%)
00:00-07:00 – 0.0 07:00-17:00 – 1.0 17:00-00:00 – 0.0	00:00-08:00 – 0.036 08:00-12:00 – 0.8 12:00-13:00 – 0.5 13:00-16:00 – 0.8 16:00-00:00 – 0.036	35W/m² 2.1m²/occ. 1.0 met 0.85±0.25 clo	5.0W/m² 12.0W/m²	+21°C … +25°C	>+16°C (without cooling)	4.2 l/(s·m²) idle 0.15 l/(s·m²)	Walls 50 Floor 20 Ceiling 70 Shading 35 Ground 20

Table 12. Room and facade parameter combinations.

Room dimensions	Envelope	Windows	Window dimensions	Orientation	Glazing g-value	Glazing VT (%)	Shading depth (hor.)
Depth, m: 5, 6, 7, 8, 9 Width, m: 5, 6, 7, 8, 9	Ext. wall: Concrete 150mm Exp.polystyr. 300mm Concrete 50mm U_{tot} 0,129W/(m²·K) Ext. window perimeter thermal bridge: 0.1W/(m·K) Fixed infiltration: 1.5m³/(h·m²)	Frame fraction 0.34 East/south/west: U_g 0.58W/(m²·K) U_{tot} 0.60W/(m²·K) East/west with shading: U_g 0.70W/(m²·K) U_{tot} 0.71W/(m²·K) North: U_g 0.61W/(m²·K) U_{tot} 0.62W/(m²·K) (north)	Recess depth 0.25m Room width, number of windows-width/height: 5m, 2-1.9/1.7m 6m, 3-1.466/1.7m 7m, 3-1.8/1.7m 8m, 4-1.45/1.7m 9m, 4-1.7/1.7m	E	0.35	0.635	-
					0.42	0.707	0.9m
				S	0.35	0.635	-
							0.9m
				W	0.35	0.635	-
					0.42	0.707	0.9m
				N	0.54	0.733	-

3 Results and discussion

3.1 Measured summertime temperatures in apartment buildings

The field measurement results of hourly mean indoor temperatures in bedrooms and living rooms are presented in Figure 20. The constant line of +27°C temperature in figures shows the maximum allowed indoor temperature limit by Estonian regulation [121] (and by the EN 15251 standard [9]). It is shown that in some cases temperatures over +30°C are experienced, giving clear evidence of overheating. Most of the periods with temperatures over +27°C occur at the end of July and at the beginning of August, during the warmer summer periods with outside air temperatures reaching +30°C as well (Figure 6, right). The calculated temperature excess $DH_{+27°C}$ for the measurement period was exceeding the 150Kh limit value in 17 out of 18 (94%) of the rooms. However, this excess rate cannot be considered as non-compliance with regulation, because of the differences in standardized simulation-based compliance procedure and the real situation in the dwellings and the differences in weather data, especially the warmer outdoor temperature compared to TRY. The highest excess value was calculated for room #10 with 2110Kh, which was two times higher than the excess for the next room in line, #16 with 1053Kh.

To analyse the design-induced reasons behind overheating risk, correlations between the indoor temperature excess and the main parameters that characterize architectural design and passive measures, which have an influence on indoor temperature, have been given.

One such measure for combating high temperatures is ventilative cooling through operable windows. To compare the passive cooling potential of different rooms, we used a parameter defined as openable area divided by the total area of the windows (OA). Comparison between the indoor temperature excess $DH_{+27°C}$ and OA show good correlation with a statistical significance $P < .01$, even without considering differences in shading or orientation (Figure 21, left). Considerably lower DH is calculated for rooms with OA higher than 0.05. The same peak levels, around 400Kh, have rooms with the maximum OA of 0.1 and in-between, suggesting that the OA should be at least 0.05 to provide sufficient airing area.

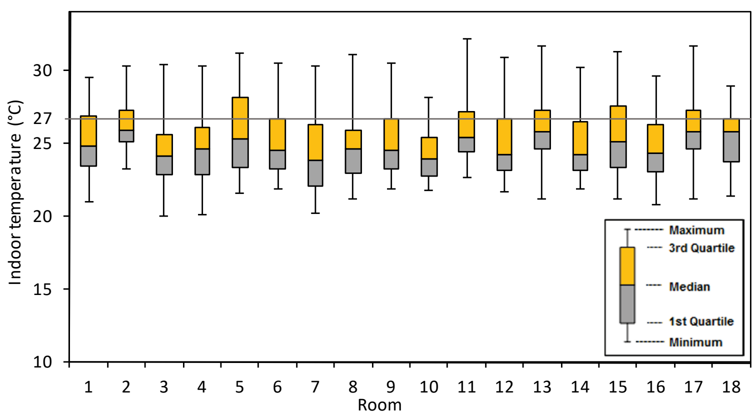


Figure 20. Measured hourly mean indoor temperatures during the period of 1 June – 31 August 2014 in studied bedrooms and living rooms.

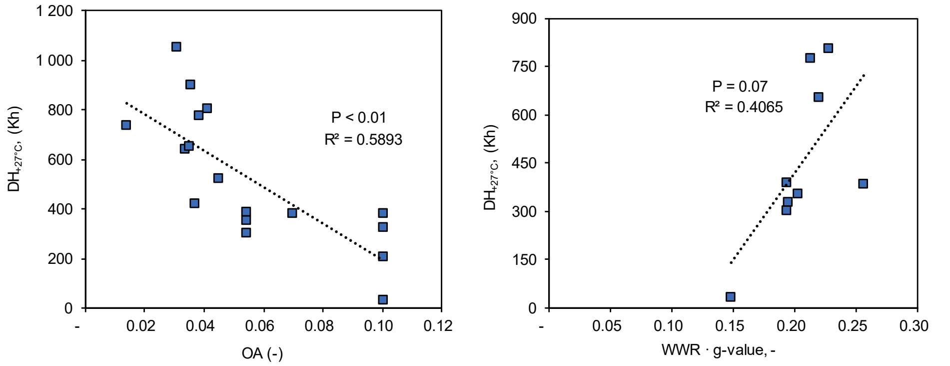


Figure 21. Indoor temperature excess $DH_{+27°C}$ dependence on openable window area to total window area (OA) (left) in all the measured rooms and on window-to-wall ratio (WWR) multiplied by window g-value (right) in south- and west-oriented rooms.

When considering other factors, such as window-to-wall ratio (WWR) and solar heat gain coefficient or g-value, no clear correlation was found. However, when limiting the selection to only south and west oriented rooms and using the combination of WWR and g-value, an acceptable correlation was achieved (Figure 21, right). The chart shows that WWR·g-value below 0.2 is recommended ($DH_{+27°C}$ < 400Kh) and less than 0.15 should be considered, but also the relatively low number of measured cases and significance of the statistical data (P = .07) need to be accounted.

3.2 Thermal zoning and model calibration

3.2.1 Model calibration

An example of a model calibration result of a living room for an eight-day long heatwave period is shown in Figure 22. The goal for the calibration was to achieve CV(RMSE) values under 5%. It is shown that the calibration results show an acceptable agreement with the measurements (Figure 23). The simulation results of the calibrated building models for two extreme cases, in terms of DH, are presented in Figure 24.

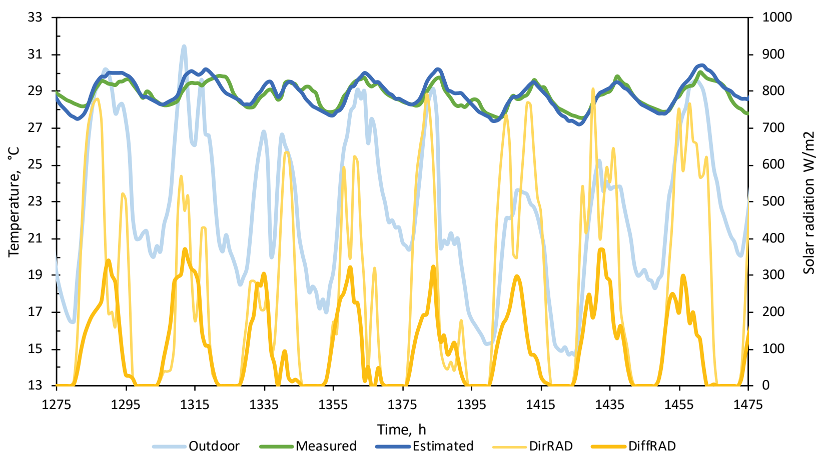


Figure 22. Model calibration results of simulated living room (building B4) temperature, 8-day period during the heatwave in 2014 summer. Code: Outdoor – ambient temperature; Measured – measured indoor temperature; Estimated – simulated indoor temperature; DirRAD – direct normal solar radiation; DiffRAD – diffuse solar radiation on the horizontal surface.

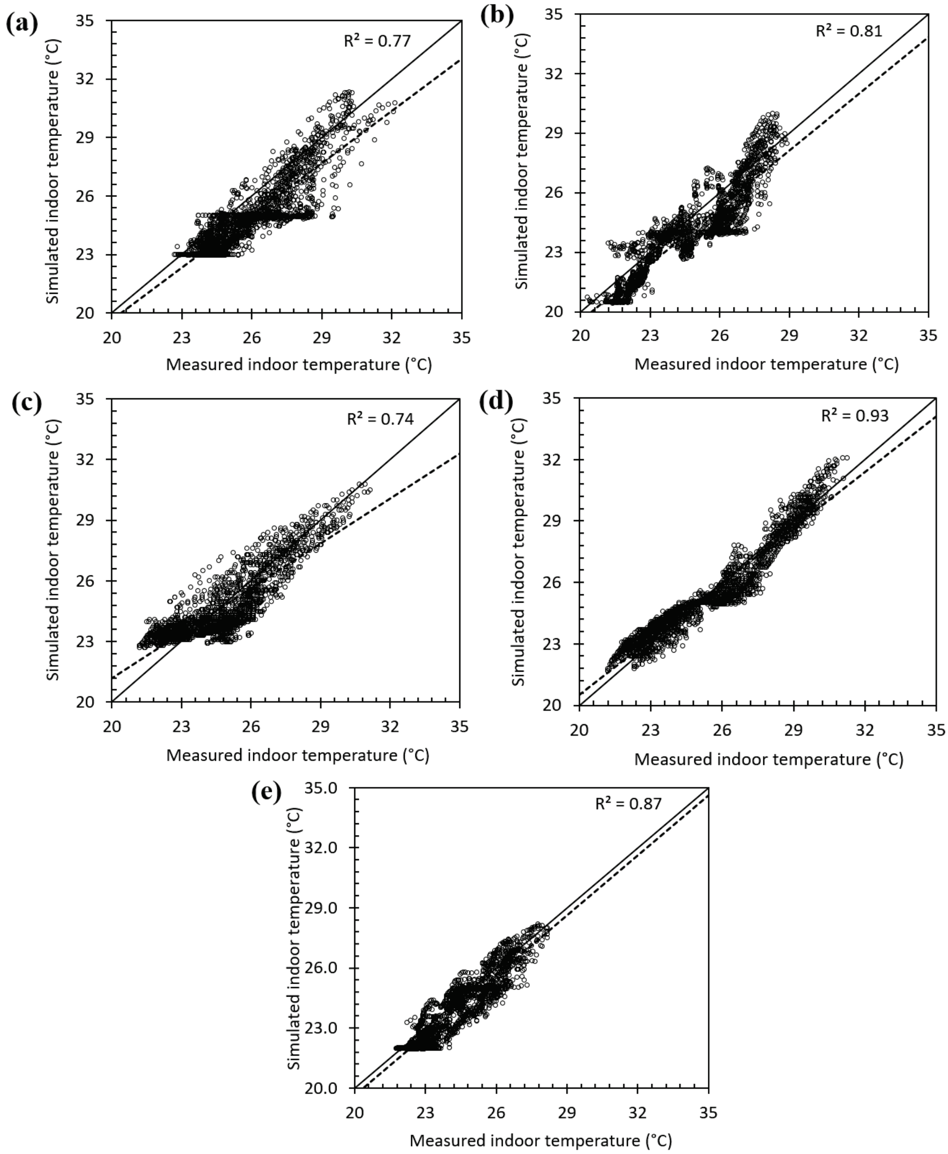


Figure 23. Model calibration results: comparison of 2208 hours of measured and estimated indoor temperature values: bedroom in building B1 (a), bedroom in building B2 (b), living room in building B3 (c), living room in building B4 (d) and bedroom in building B5 (e).

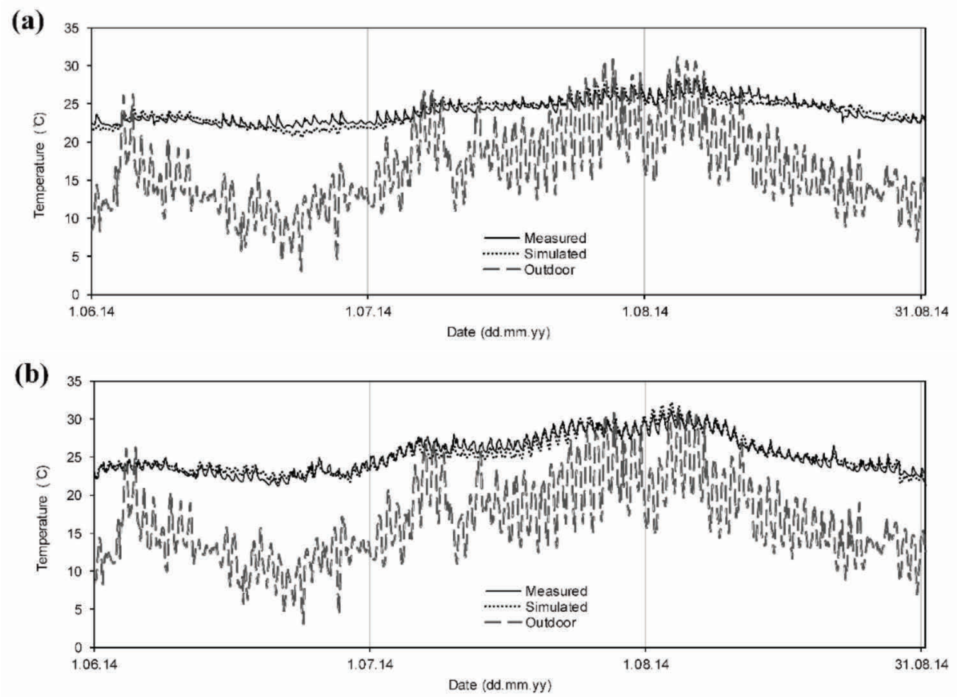


Figure 24. Examples of model calibration results: measured and simulated hourly-average indoor temperature in selected rooms during the summer period of 1. July to 31. August 2014. Room with the lowest measured temperature excess (DH) – bedroom in building B5 (a) and room with the highest measured DH: living room in building B5 (b).

3.2.2 Thermal zoning impact on room temperature and overheating results

The largest whole building model, with 153 thermal zones, was created for building B3, which had 40 apartments. The simulation time for this model, using a high-performance personal computer (housing an Intel© Core™ i7-5820K processor), was 3 hours and 14 minutes. In comparison, for the apartment-based model with three zones, the simulation time was 1 minute and for the single-zone model, 8 seconds.

The calculated simulation evaluation parameters from different thermal zoning methods are shown in Table 13. The average error increases, when simplifications are applied to the whole building models. It can be seen that although CV(RMSE) values in full apartment simulation method and single-zone method remain in similar proportions, the average error percentage is over 10% in four of the whole apartment model cases and single-zone model cases. Results acquired using the single-zone method show mostly lowest agreement with the measurement results, however being close to the apartment-based cases. In four of the cases, comparing apartment and single room modelling results, the single room cases give higher DH values, except for the case with building B4, in which the single room method gives lower value. The small change in error values, regarding building B5, could be accounted for the shade casting neighbouring buildings and trees, limiting the effect of direct solar radiation to the building.

Table 14 shows the difference between using standard values for occupant profiles and internal gains according to the methodology [122] and real thermal situation trough measurements in the studied rooms. The whole building model and apartment model give mostly lower DH results, as the single-zone method gives higher values for the cases with lower measured DH.

Table 13. Evaluation results of the indoor temperature simulations for different modelling detail.

Building No.	Avg. Error, (%)	Avg. Dif., (K)	Avg. Bias, (K)	CV(RMSE), (%)	MBE, (%)	$DH_{+27°C}$, (Kh)
Measured						
B1	-	-	-	-	-	777
B2	-	-	-	-	-	209
B3	-	-	-	-	-	354
B4	-	-	-	-	-	1053
B5	-	-	-	-	-	35
Calculated: Whole building model (calibrated)						
B1	7.6	0.8	1.6	4.7	-2.5	765
B2	9.9	0.9	1.3	4.3	-2.1	211
B3	9.6	0.8	1.0	4.1	-0.2	360
B4	5.5	0.6	0.4	1.8	0.1	1065
B5	6.0	0.6	0.5	2.1	-1.5	50
Calculated: Apartment model (neighbouring zones removed)						
B1	11.7	1.1	1.7	6.7	-3.7	535
B2	13.7	1.2	2.0	7.9	-3.6	265
B3	10.3	0.9	1.2	5.0	1.9	277
B4	13.9	1.4	3.2	12.4	-4.5	813
B5	6.6	0.6	0.5	2.2	-1.5	29
Calculated: Single-zone model (neighbouring zones removed)						
B1	12.5	1.1	1.7	6.7	-3.3	641
B2	13.8	1.2	2.0	7.9	-3.2	448
B3	12.1	1.0	1.9	7.6	3.4	936
B4	17.5	1.5	3.6	14.2	-5.1	676
B5	7.6	0.7	0.7	3.0	0.4	230

Table 14. Evaluation of simulated temperature results for different thermal zoning methods using standard values according to the methodology [122] and climate data from summer 2014. Code: MEAS – measured room; BLD – whole building model; APT – apartment model; SZ – single-zone model.

Building, room	B1, bedroom				B2, bedroom				B3, living room				B4, living room				B5, bedroom			
Thermal zoning	MEAS	BLD	APT	SZ	MEAS	BLD	APT	SZ	MEAS	BLD	APT	SZ	MEAS	BLD	APT	SZ	MEAS	BLD	APT	SZ
$DH_{+27°C}$, (Kh)	777	478	535	641	209	190	152	358	354	298	277	936	1053	527	813	676	35	29	39	230
Min temp. (°C)	22.7	23.0	23.0	22.9	20.3	20.4	20.4	20.4	21.2	21.9	21.9	22.0	20.3	20.9	19.2	19.2	21.7	22.0	22.0	21.9
Max temp. (°C)	32.1	31.3	31.7	32.5	28.9	29.9	29.6	30.7	31.1	30.5	30.4	32.7	31.2	30.4	31.7	31.6	28.2	27.9	28.2	30.4
Avg temp. (°C)	25.8	24.9	24.9	25.0	24.8	23.1	23.0	23.2	24.7	25.2	25.2	25.5	25.3	25.3	24.3	24.1	24.1	23.7	23.7	24.2
Avg. Error, (%)	-	12.7	9.9	12.6	-	21.0	21.2	20.8	-	10.2	10.5	12.3	-	7.1	10.5	15.0	-	7.0	5.3	7.6
Avg. Dif., (K)	-	1.1	1.1	1.1	-	1.8	1.8	1.8	-	0.9	0.9	1.1	-	0.8	1.2	1.3	-	0.6	0.6	0.7
Avg. Bias, (K)	-	1.8	1.7	1.7	-	4.5	4.6	4.3	-	1.2	1.3	1.9	-	0.9	1.9	2.4	-	0.5	0.5	0.7
Max. Dif., (K)	-	4.5	4.5	4.5	-	4.8	4.8	4.3	-	3.5	3.5	4.5	-	3.2	3.4	3.7	-	2.3	2.2	2.7
CV(RMSE), (%)	-	6.8	6.7	6.8	-	18.3	18.5	17.5	-	4.9	5.1	7.7	-	3.7	7.6	9.6	-	2.2	2.1	2.9
MBE, (%)	-	-3.8	-3.6	-3.4	-	-6.9	-7.1	-6.3	-	2.0	2.1	3.5	-	-0.1	-4.2	-4.9	-	-1.6	-1.6	0.3

Three of the DH values for single-zone models (B1, B3 and B4), modelled and simulated according to the Estonian methodology [122], are higher compared to the multi-zone model results (Table 15). However, in two cases (B2 and B5), the single-zone model gives lower values. This occurs most likely because of the high temperatures in the neighbouring zones, which is not accounted, in case of the single-zone model, or thermal load shifting due to the movement of the sun and the effect of direct solar irradiation. As the standardised, single-zone simulation results define also the compliance according to the current methodology, it can be seen that rooms, which encountered remarkable overheating in reality, show also non-compliance with the single-zone simulations. The whole building model and apartment model however, in case of building B1, do not show non-compliance. The latter case, also when comparing simulations made with climate data from 2014, can be explained with higher in internal gains, closed doors between the rooms or lack of window airing in practice, during the measurement period.

Table 15. Evaluation of simulated temperature results for different thermal zoning methods using standard profiles and climate data from TRY; Code: BLD – whole building model; APT – apartment model; SZ – single-zone model.

Building, room	B1, bedroom			B2 bedroom			B3 living room			B4 living room			B5 bedroom		
Thermal zoning	BLD	APT	SZ	BLD	APT	SZ	BLD	APT	SZ	BLD	APT	SZ	BLD	APT	SZ
$DH_{+27°C}$, (Kh)	60	79	189	0	8	0	10	7	55	218	267	319	0	0	0
Min temp. (°C)	22.9	22.9	20.2	19.6	20.4	20.5	22.4	22.5	22.2	24.3	24.2	23.8	21.8	21.8	21.9
Max temp. (°C)	28.7	28.9	30.7	26.6	27.4	26.9	27.7	27.6	28.6	29.0	29.3	29.7	26.4	26.5	26.8
Avg temp. (°C)	24.7	24.7	23.8	22.3	22.6	22.6	24.9	24.9	25.0	26.2	26.2	26.2	23.5	23.5	24.1
Avg. Error, (%)		0.8	13.5		8.2	5.0		0.7	2.9		0.7	1.4		2.1	7.1
Avg. Dif., (K)		0.1	1.1		0.7	0.4		0.1	0.2		0.1	0.1		0.2	0.6
Avg. Bias, (K)		0.0	1.5		0.7	0.4		0.0	0.1		0.0	0.0		0.0	0.5
Max. Dif., (K)		0.5	2.8		3.5	3.7		0.3	2.5		0.5	1.3		0.6	1.6
CV(RMSE), (%)		0.0	6.0		3.0	1.8		0.0	0.6		0.0	0.1		0.2	2.0
MBE, (%)		0.1	-3.5		1.1	1.3		0.2	0.6		0.2	0.1		-0.7	2.5

Code: BLD – multi-zone whole building model; APT – multi-zone apartment model; SZ – single-zone model.

3.3 Developing overheating assessment methodology for existing buildings

Although overheating assessment by calculations for a building in the planning stage is required with the state regulations in order to acquire a building permit, the importance of this procedure is often underestimated and calculations are usually done poorly, if at all [156]. In such cases, it is difficult for the tenant to prove the existence of the problem, as it is only defined as a requirement and a method for evaluating building designs and not as an assessment for existing buildings. If the calculations have not been conducted, the acquisition of input data, regarding envelope structures, technical drawings etc. can be difficult. For such cases, estimating the simulation results, based on real indoor temperature measurements, could act as an efficient and low-cost method.

Different studies have indicated that there is a relatively strong correlation between outdoor and indoor air temperatures at higher ambient temperatures [13, 157]. Every degree of outdoor temperature increase is found to increase the indoor temperature 0.29K … 0.43K [158, 159]. As the outdoor temperature has an important effect, still the main influence on indoor temperature has direct and diffuse solar radiation through windows, internal heat gains, occupancy and the behaviour of the occupants [160]. The correlation between measured indoor temperatures and outdoor temperatures is presented in Figure 25. The figures are constructed for lowest and highest correlation between outdoor and indoor temperature.

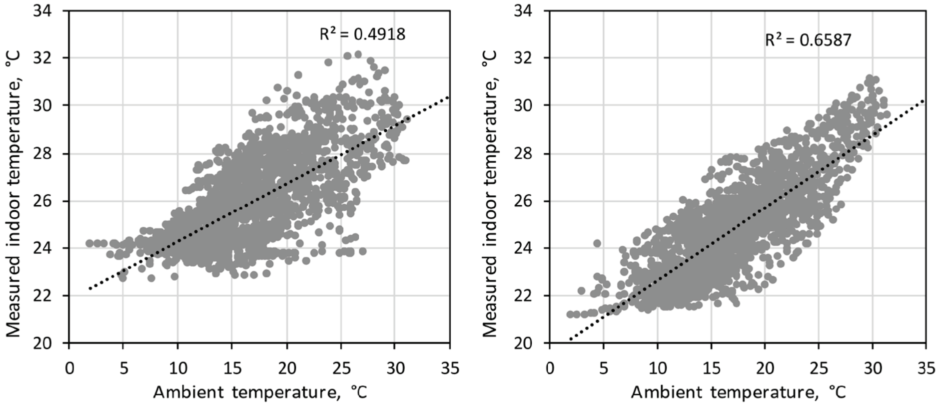


Figure 25. Correlation between measured hourly average indoor temperature and ambient temperature values during the three-month measurement period for two analysed rooms. Lowest linear correlation (left) was found for bedroom in building B1 and highest (right) for living room, building B3.

The measured DH for the studied rooms' dependence on the base temperature change is shown in Figure 26.

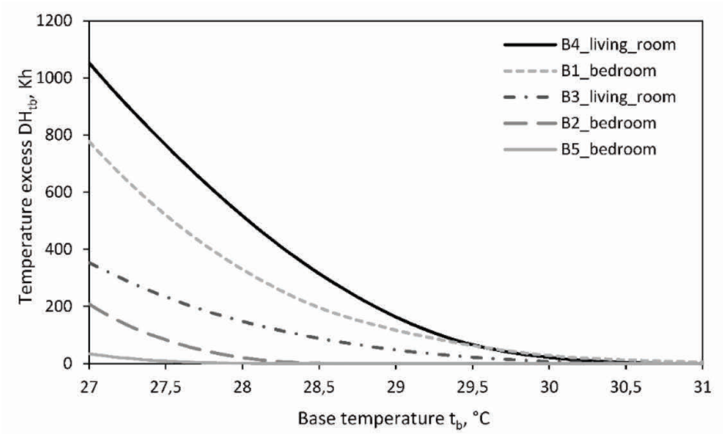


Figure 26. Measured temperature excess (DH) dependence on base temperature t_b in the analysed rooms during the summer period of 2014.

The main sources of uncertainty in terms of input parameters used in computer simulations estimation indoor temperatures are weather data, including solar radiation and temperature, building envelope properties, internal heat gains and occupant behaviour [119, 161]. Because of the latter, it is reasonable to use methods which do not underestimate overheating risk [161].

The proposed equation, to act as a 'rule of thumb', for correcting the real year base temperature for DH calculations, to make measured room temperature values comparable to standardized calculations, is given as:

$$t_{b,n,corr} = t_b + \frac{DH_{t_b,n}}{105} \tag{12}$$

where $t_{b,n,corr}$ is the corrected base temperature for year n, t_b is the base temperature used in standardized calculations, $DH_{tb,n}$ is the outdoor DH in degree-hours over the base temperature t_b for the measured year and the value 105 is the proposed constant with a reasonable safety factor accounting for the difference in climate data for a real year compared to TRY.

The example using the equation is presented in Figure 27. In the case of the summer of 2014, the correction for base temperature, is 1.5K (for t_b = +27°C and $DH_{+27°C,\ 2014}$ = 157Kh) and the corrected base temperature t_b = +28.5°C. For all the cases, the corrected measured values are higher, than the regulations based on simulated DH values.

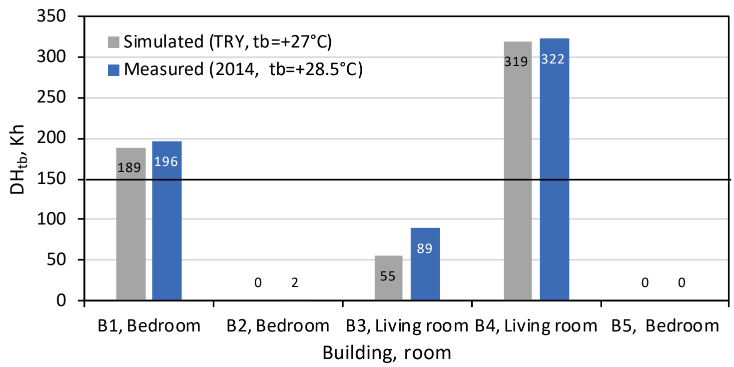


Figure 27. Comparison between measured temperature excess (DH) (summer of 2014) with corrected base temperature t_b = +28.5°C and simulated DH with base temperature t_b = +27°C. The 150Kh line indicating the threshold for compliance.

3.4 Effective measures for overheating prevention

From the total of 158 simulated bedrooms and living rooms, 52 reached indoor temperature excess $DH_{+27°C}$ values higher than 150Kh, the same number of rooms had no temperature excess and the rest (N=54) had $DH_{+27°C}$ values in between. The temperature duration curves for all the simulated rooms are shown in Figure 28. In some cases, temperatures below 19°C were experienced, as during the summer, room heating is not used, and it was also not accounted in the simulations. In Figure 29, 'worst-case' rooms for each building have been presented. Altogether in 17 out of 25 (68%), simulated buildings temperature excess $DH_{+27°C}$ in at least one of the bedrooms or living rooms exceeded the limit value of 150Kh, meaning that the building can be considered non-compliant according to the Estonian regulation [121]. As for the standardized simulations, internal gains from occupants, lighting and equipment, as well as ventilation airflow rates per floor area, are identical across all the different buildings, and the large differences in temperature excess are caused mainly due to solar heat gains. In higher buildings, shades from other structures and foliage do not reach the upper floor dwellings, resulting in constant exposure to direct solar radiation. Large glazing areas with clear glazing, in combination with small openable windows, can result in extremely high indoor temperatures, as was the case with building B13.

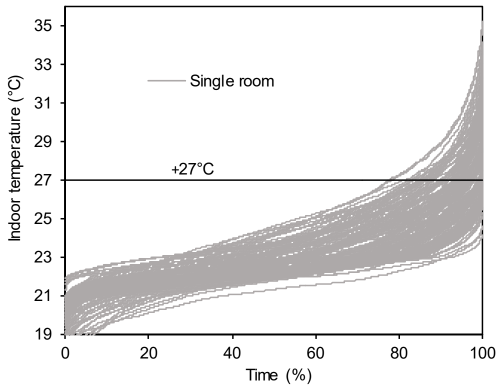


Figure 28. Simulated cumulative indoor air temperature in living rooms and bedrooms.

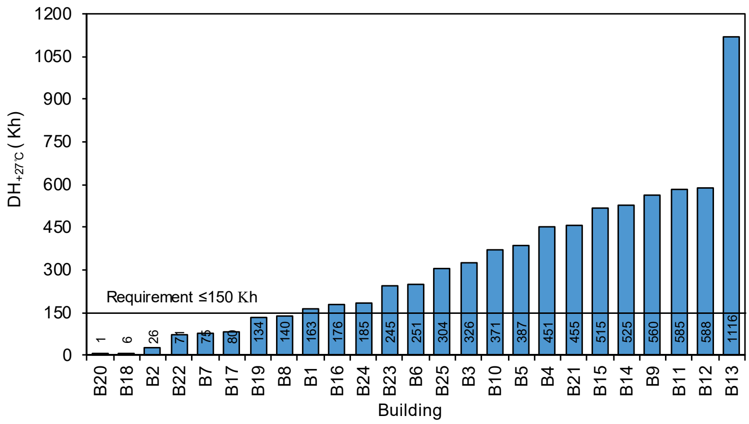


Figure 29. Simulated room temperature excess $DH_{+27°C}$ in 'worst-case' rooms in studied apartment buildings during the period from 1 July to 31 August. Requirement for compliance is ≤150Kh [121].

When comparing measurement results to simulation results, it has to be accounted that there are many important variables, which are influencing the results and are disregarded in the standardized simulations made according to the methodology, aside from the weather data differences. Research shows that occupants' behaviour is not deterministic [99, 162-165]. For example, occupancy density and presence profile, which affects internal heat gains as well as opening and closing windows, which can have a substantial effect on the indoor temperature. Also, as we did not track occupants' presence in dwellings, it is possible, that during the warmer periods, the dwelling was unoccupied and windows were not operated, resulting in higher temperature excess values for the measured cases (Figure 30). It can be seen that in some cases the temperature excess values between the measured and simulated cases can be similar (e.g. room #22) as well as slightly (room #14) or significantly (room #8) different, with mostly higher values for measured cases.

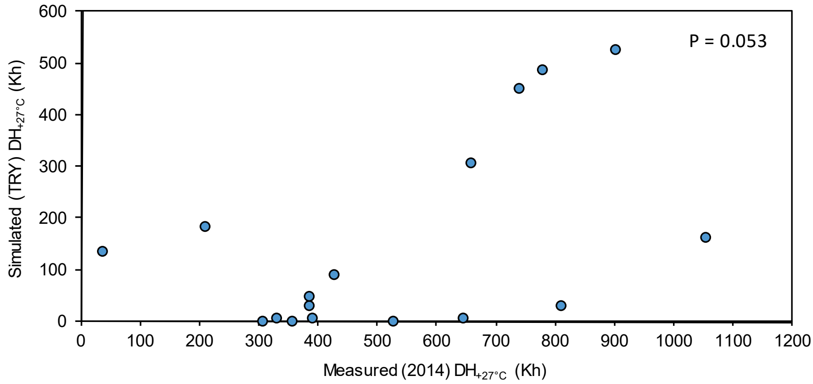


Figure 30. Correlation of temperature excess $DH_{+27°C}$ in dwellings between measurements, conducted in summer 2014, and simulations using climate data from Estonian TRY.

To some extent, it is an indication of the room use and window opening operations, which can be close to the standard-use profile. Although most cases gave higher excess values with measurements, which to some extent could be explained with higher outdoor temperatures during the measurement period in 2014 compared to TRY (Figure 4), resulting, in an average, 300-400Kh higher temperature excess.

In order to better compare the simulated rooms and to illustrate the effects of different parameters, in some cases we included also simulated rooms in which temperatures did not reach the +27°C mark, by using a lower base temperature of +25°C ($DH_{+25°C}$) for calculating the temperature excess.

Indoor temperature simulation results, when looking at the rooms with $DH_{+27°C}$ <0 (Figure 31, a), show practically no correlation between the indoor temperature excess and OA; in case of rooms with 0<$DH_{+27°C}$ <150Kh (Figure 31, b) we can see weak correlation, and for rooms with $DH_{+27°C}$ >150Kh (Figure 31, c), there is a relatively strong correlation with good statistical significance, showing that in rooms with high overheating risk, larger openable window area can decrease the indoor temperature excess.

In Figure 32, the dependence between the temperature excess $DH_{+25°C}$ and WWR·g-value is shown. In rooms with external shading elements, there is no significant correlation, whereas in rooms without external shading, the higher WWR·g values result also in higher temperature excess values. Roughly, WWR·g value lower than 0.2 shows similar temperature excess values with shaded rooms.

Figure 33 illustrates the influence of WWR in the south- and west-oriented rooms with external shading (left) and without external shading (right). In addition to what previous comparison indicated, the use of shading elements has a significant impact on higher room temperatures, resulting in lower temperature excess values and, in most cases, lower the overheating risk, in case of larger windows. Another important variable, as also found in the case of measurements, is OA (Figure 33, right). Higher OA values, in combination with low WWR and no shading, result also in lower temperature excess values. In this case, OA over 5% and WWR under 0.4 give similar results with shaded variants. Rooms with a combination of WWR less than 0.3 and OA greater than 10% show very low excess values, even with the base temperature of +25°C.

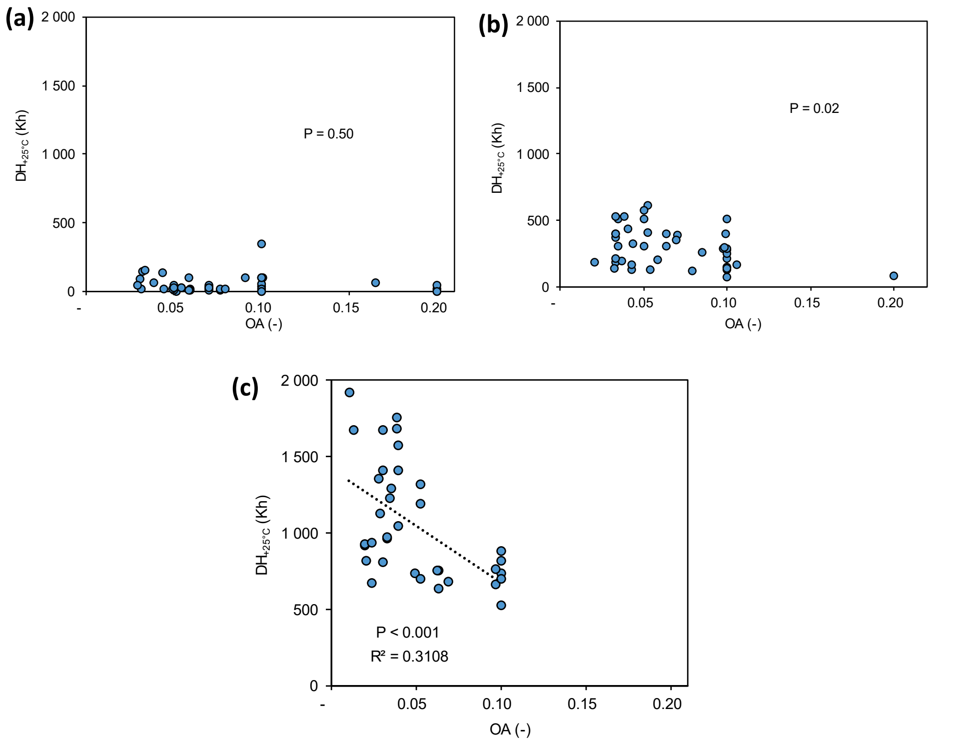


Figure 31. Dependence between the simulated indoor temperature excess $DH_{+25°C}$ and openable window area to total windows area ratio (OA) in rooms with the calculated temperature excess over +27°C of 0Kh (a), <150Kh (b) and ≥150Kh (c).

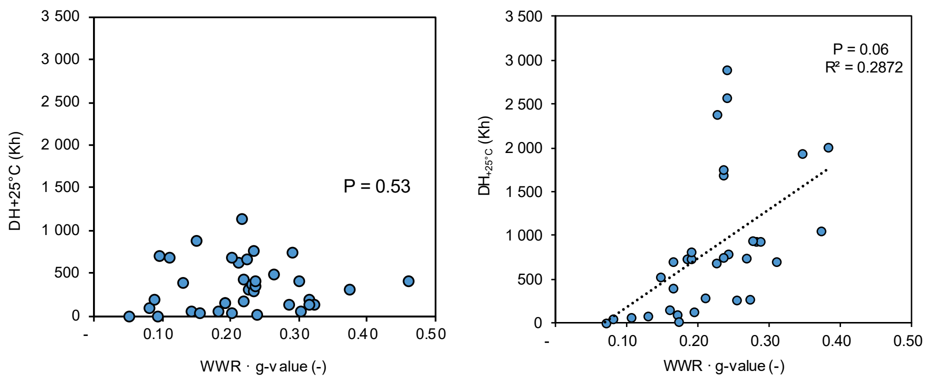


Figure 32. Simulated indoor temperature excess $DH_{+25°C}$ dependence on the window to floor area ratio (WWR) multiplied by window g-value in rooms with external shading elements (left) and without shading (right).

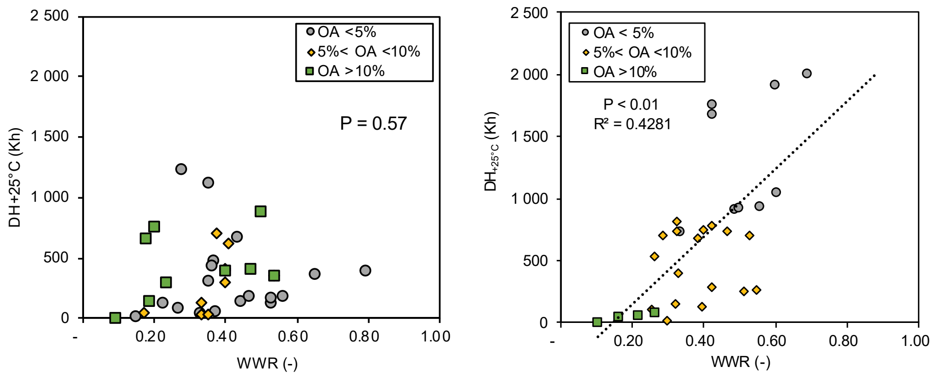


Figure 33. Simulated indoor temperature excess $DH_{+25°C}$ dependence on the window to wall ratio (WWR) in south and west oriented rooms with external shading elements (N=37) (left) and without shading (N=35) (right). Total openable area ratio of windows (OA) is shown in three percentage levels.

When no intentional shading options are introduced – as was the case in almost every studied building – balconies can act as the most effective shades. In south-facing rooms, with high sun elevation during summer, balcony overhangs can contribute the most to direct sun radiation blocking. In west-facing rooms, on the other hand, the sun elevation is low, so left-sided fins have the biggest effect in case of balconies (Figure 34). In order to have a significant shading effect, it is considered that for overhangs, the ratio of overhang length 'L' divided by the height from overhang to the lowest part of the window 'H', was found to be at least (L/H=) 0.7 and for side-fins, the ratio of side-fin length 'B' divided by width from side-fin to the farthest side of the window 'C' as well was at least (B/C=) 0.7 (Figure 34). In this case, the purpose is not to fully block direct sunlight, but to reduce it for sufficient amount. Of course, better results can be achieved by using specific shading, for example, external or between-the-panes horizontal venetian blinds for south façade windows and vertical blinds for west façade windows, to ensure maximum shading and minimal negative effect on daylight and outside view. In Figure 35, box plot of simulated temperature excess $DH_{+27°C}$ in rooms with different orientation and shading is given. Most problematic are west oriented rooms with no shading, with every case over the allowed limit, but also rooms with too short side-fins or wide windows (B/C<0.7). In south-oriented room cases, the results are similar for rooms without shading and rooms with insufficient shading overhangs with L/H<0.7. In both south- and west-oriented rooms, using sufficient shading, with L/H>0.7 and B/C>0.7, respectively, results in acceptable indoor temperature excess. In every case, in the north- and east-oriented rooms, the temperature excess was below the requirement limit. This can be explained with the low levels of direct solar radiation in north orientation and lower outdoor temperatures in the morning in east-oriented rooms.

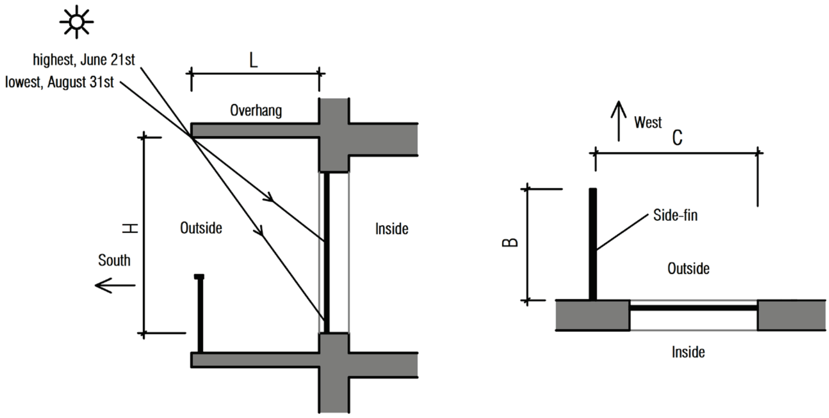


Figure 34. Examples of effective shading. For south-facing windows: (balcony) overhang with L/H > 0.7 (left) and for west-facing windows: (balcony) side-fin with B/C > 0.7 (right).

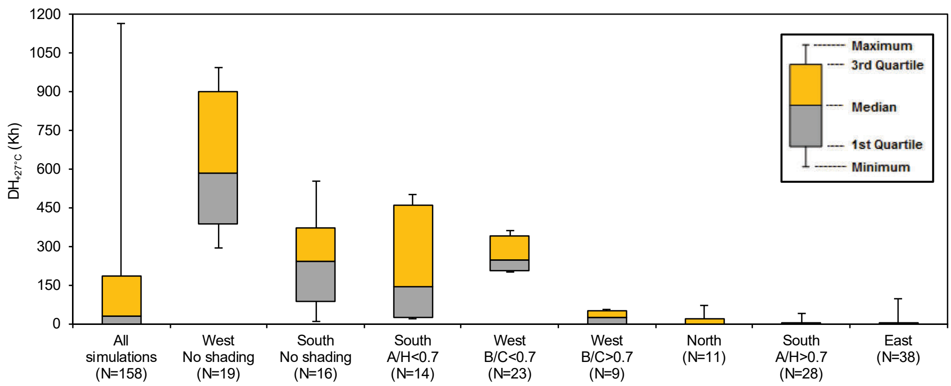


Figure 35. Simulated indoor temperature excess $DH_{+27°C}$ in dwellings: influence of orientation and shading. N – number of simulated rooms.

3.5 Daylight and sunlight combined analysis for overheating prevention

3.5.1 Insolation and overheating risk assessment

Figure 36 illustrates the differences in insolation duration calculation results for unshaded windows between the Estonian Standard [66] and the proposed European Standard [126] methods. Results are given for 21 March and April. It is shown that the duration calculated according to Estonian Standard is 1.65h in March and 1.46h in April longer than according to the calculation results of the European Standard. As the European Standard has a minimum insulation duration of 1.5h, it is possible to guarantee the duration in March. Achieving 2.5h insolation is also possible in April, but the useful period according to the European Standard is 1.5h less.

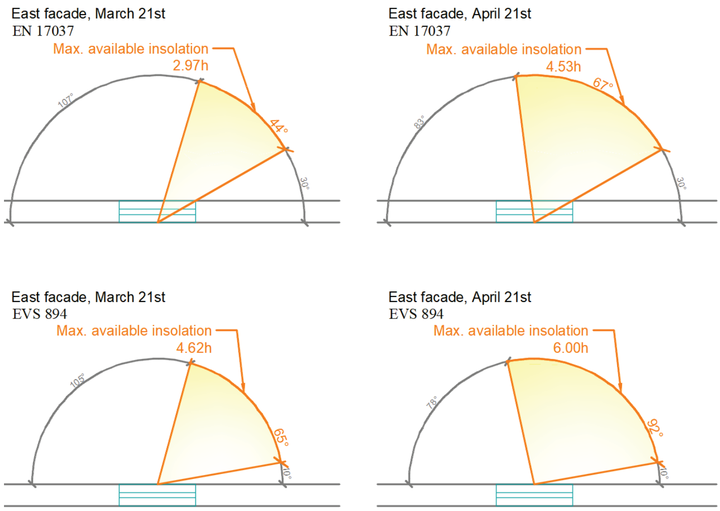


Figure 36. Comparison between maximum available insolation duration calculated according to the standards EN 17037:2019 [126] (top) and EVS 894:2008/A2:2015 [66] (bottom).

In Figure 37 it is described the time at which the insolation begins and ends, the height angle and the duration of the insolation on the east and south oriented façades. In April and August, the Sun's trajectory is identical, so the altitude and azimuthal angles also coincide. The insolation duration of the eastern (and western) façades limits the sun's altitude in addition to the façade design.

The east and west oriented façades have a minimum solar altitude of 6.0° in unshaded conditions. The maximum height angle differs from the maximum solar altitude for the south façade because the minimum solar altitude for the assessment is 10°.

The critical depth of overhanging balcony on the south façade windows, considering the height from floor to the balcony overhang of 2.74m, for 21 April and 21 August is L_r = 2.0m and for June 21st is L_r = 1.3m. The average decrease of insolation duration for different façades in April, August and June design days are shown in Figure 38. It is shown that the balconies reduce insolation time more in June than in April or August, as they obscure direct sunlight at high solar altitudes. The average insolation duration decreases with the increase in balcony depth. On average, a 0.6m deep balcony reduces insolation duration by 27%, 0.9m by 36%, 1.2m by 41% and 1.5m by 52%. In case of a 1.5m deep balcony, the decrease in insolation duration is on average 69%, but in the case of south-oriented façade, the decrease is 100%.

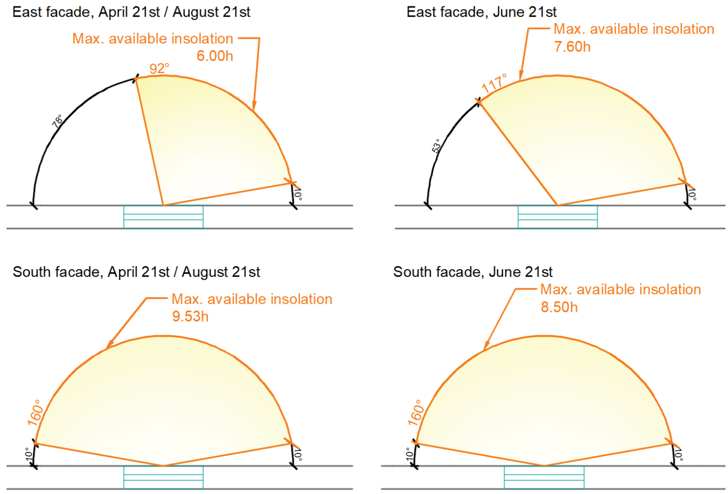


Figure 37. Maximum continuous insolation duration for east (top) and south (bottom) façade during spring/autumn and summer design days.

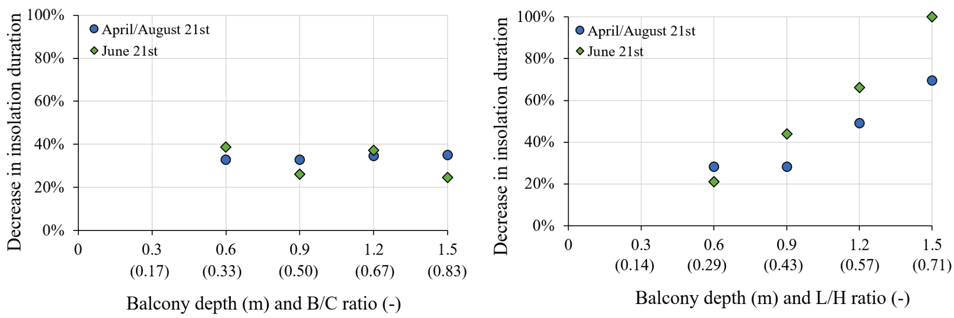


Figure 38. Average decrease of insolation duration for balcony depths up to 1.5m during April/August 21st and June 21st for the eastern and western facade (left) and southern facade (right). For south (left) orientation, overhang L/H ratios and for west orientation(right) side-fin ratios B/C are shown.

These results pose a conflict between the requirements in daylight standards and national requirements regarding overheating prevention, making it difficult to achieve both sufficient insolation and minimize the risk of unacceptably high indoor temperatures in mostly south-oriented facade cases.

Due to the early sunrise in June, the maximum insolation duration is available on the eastern and western façades in mid-summer. The change in the azimuth angle, which must guarantee 2.5h insolation on the eastern and western façades, is the same in April and June, as the range of azimuth angle increases. At the same time, the length of the insolation period on mid-summer on south facade is shorter than in April, and the required change in azimuth angle to ensure insolation is 2.5h is greater. The maximum elevation angles in south, east and west façades are higher in June than in April. Thus, it would be wise to determine the duration of insolation in April, based on the change in the azimuth angle necessary to ensure sufficient insolation duration.

3.5.2 Indoor temperatures

The indoor climate simulation results present a clear correlation between balcony depth and room temperature, especially if window airing is not used (Figure 39). It can be seen that even 0.6m balcony can reduce the maximum hourly temperature by 3.3K. Further reduction in maximal temperature is 3.5K/m and in median 2.0K/m with the increase of balcony depth. The median and mean temperatures for all cases for the simulation period were roughly the same, differing less than 0.1K. For unshaded conditions, there is marginal difference in temperature distribution between bedrooms with south and west oriented windows. For south-oriented windows, balcony depth has a higher effect than for west orientation, indicating that in terms of shading, balcony design and selection of window parameters for western facades could require more careful analysis.

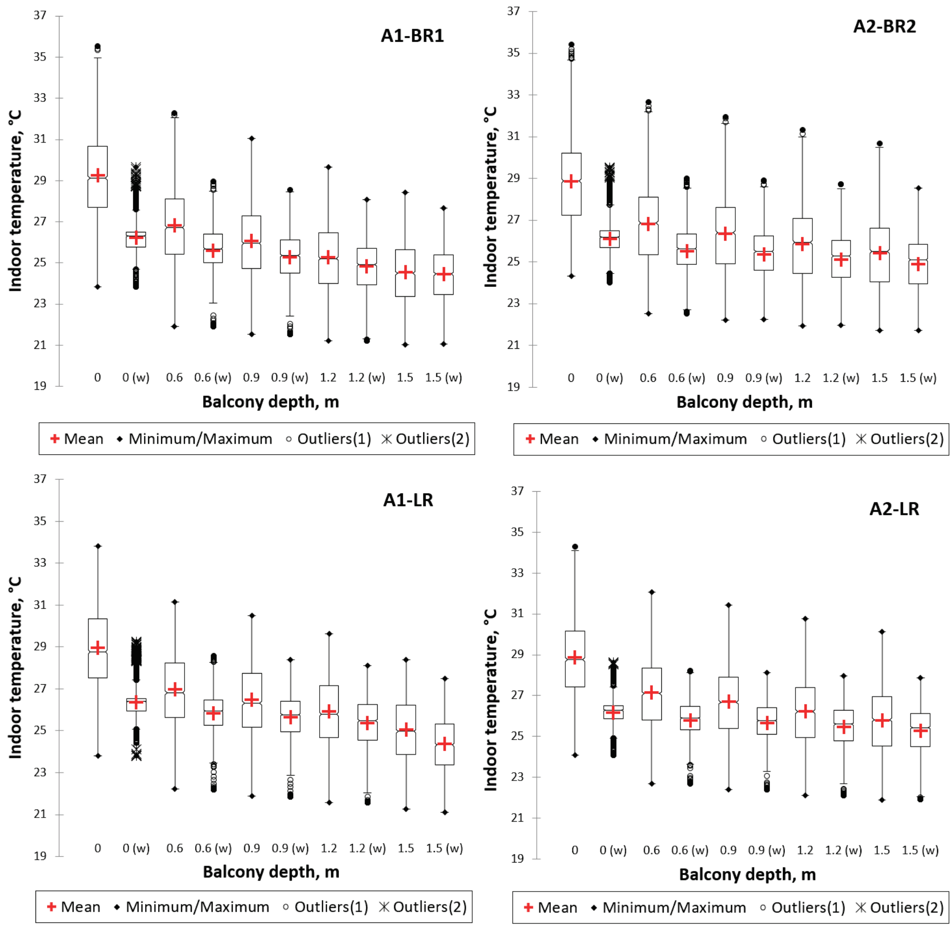


*Figure 39. Simulated hourly indoor temperature distribution for different balcony depths in case of the south (A1-BR) and west (A2-BR2) oriented bedrooms (top) and east/south (A1-*LR*) and south/west (A2-LR) oriented (bottom) living rooms without and with the use of window airing (w).*

Comparison between living room and bedroom temperatures reveal that the smaller-size bedrooms experience higher temperatures, especially in unshaded conditions. Furthermore, the effect of window airing can be substantial, especially when shading balconies are not used. The results for unshaded cases simulated with thermostat-controlled window opening macro show that the temperatures rise rapidly when direct solar radiation reaches the room and frequent window opening operation is required. In a realistic scenario, the windows need to remain open during most part of the daytime. This indicates that the ventilative cooling effect itself may not be sufficient to prevent rooms from overheating. For the selected cases, the reduction in temperature maximums when using window airing was between 4.5K and 5.9K; and the median temperature was reduced by 2.4…2.8K. Therefore, the combination of both external shading and window airing is usually required to maintain lower room temperatures.

3.5.3 Temperature excess and insolation

Figure 40 shows that the decrease in the temperature excess on the south-facing rooms is more closely correlated with the insolation duration in June than in April or August (the insolation duration hours for April and August are identical).

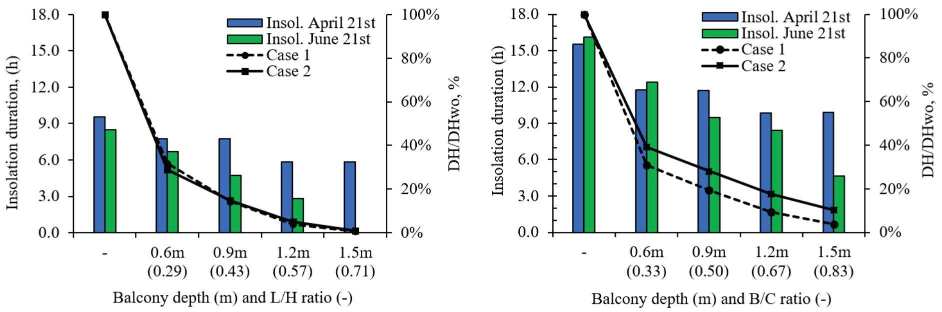


Figure 40. Continuous insolation duration for different depth balconies and DH relative to DH without balconies (DH_{wo}) for different balcony layouts (Case 1 and 2) in case of the south (left) and west (right) oriented rooms. For south (left) orientation, overhang L/H ratios and for west orientation(right) side-fin ratios B/C are shown.

Figure 40 illustrates the reduction in insolation duration and temperature excess for different depth balconies in the case of south and west oriented bedrooms for the two balcony cases. It can be seen that the reduction of DH is in correlation with the insolation duration.

For south-oriented rooms, a 0.6m deep balcony (L/H=0.29) reduces the maximum possible insolation duration in April and August, by 1.75h in case 1, and 2.68h in case 2. For June 21^{st}, the reduction is 1.8h for case 1 and 1.78h for case 2. The 0.6m deep balcony overhang causes 7% lower insolation duration during June 21^{st} compared to the case without an overhang. Same depth balcony on April 21^{st} reduces direct sunlight 5% for case 1 and 9% for case 2 compared to unshaded cases. From June 1^{st} to August 31^{st} the total direct solar radiation on the windows decreases with a 0.6m deep balcony 30% for case 1, resulting in 67% DH reduction. For case 2 a 0.6m deep balcony reduces direct solar radiation by 36%, resulting 71% in DH reduction. At the Insolation observation point, the difference in total solar radiation between the cases without shading and balcony variants is 6% for case 1, and 8% for case 2.

3.5.4 Daylighting

Calculations show that in order to ensure mDF ≥ 1.5% in the given bedroom, the visible sky angle should be at least 53 degrees. Adding a 1.2m balcony overhang, the required angle shifts 33 degrees towards the horizon (Figure 41). In the latter case the overhang L/H ratio is 0.62.

To achieve mDF ≥ 1.5% with a 1.2m overhang, the necessary angle of view of the visible sky Θ is greater than the range of solar altitude γ_s required to ensure maximum insolation duration. In the determination of the insolation duration, the range of solar azimuth needs to be accounted as well. However, by ensuring mDF ≥ 1.5%, the range of solar altitude required for sufficient insolation duration (>2.5h) due to overhang shading is also ensured (42° for southern façade and 38° for eastern and western façades). The results for different rooms are shown in Table 16.

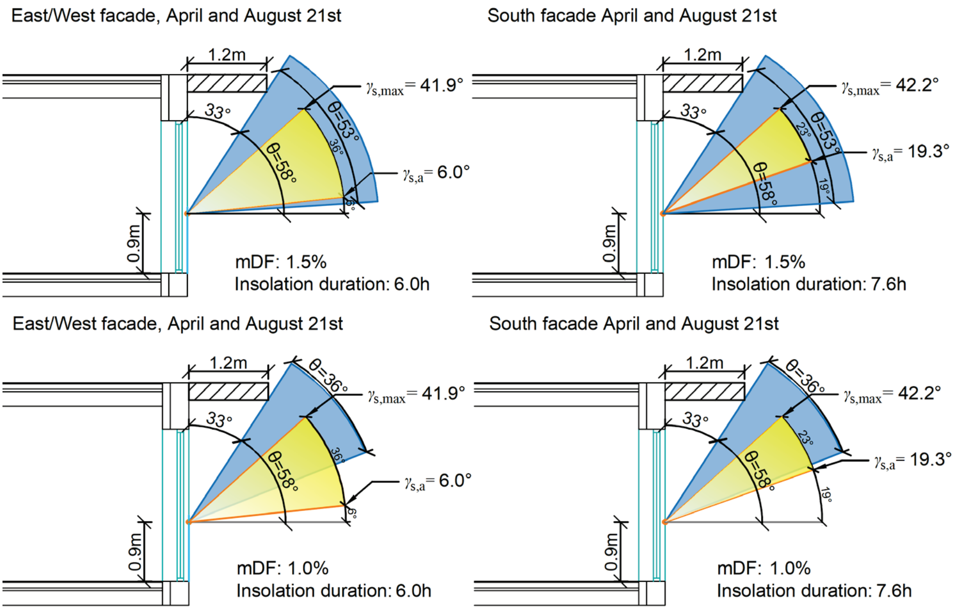


Figure 41. Available (yellow area) and required (blue area) azimuth angles for achieving mDF≥1.5% (top) and mDF≥1.0% (bottom) with 1.2m overhang in east/west and south oriented rooms according to the methodology described in Estonian Standard EVS 894 [66].

Table 16. Mean daylight factor (mDF) results for different balcony overhang depths.

Room code	mDF (%)				
	w/o*	0.6m	0.9m	1.2m	1.5m
A1-LR	**2.84**	**2.40**	**2.13**	**1.86**	**1.62**
A1-BR1	**2.11**	**1.92**	**1.71**	**1.48**	**1.28**
A2-LR	**2.56**	**2.25**	**1.99**	**1.76**	**1.56**
A2-BR2	**1.43**	**1.32**	**1.18**	**1.02**	0.87
A2-BR1	**2.07**	**1.95**	**1.75**	**1.50**	**1.26**

*without balcony

The calculation results show that the mDF requirement for up to 1.2m deep balconies is met in most rooms. However, room A2-BR2 does not meet the criteria of mDF >1.5%, even in unobstructed case. With WWR 0.15 and WFR 0.10, the room also does not meet the dwelling window size requirements for WFR ≥ 1:8 [66]. In comparison, in case of A2-BR1, WFR is 0.14, which meets the requirement. For mDF > 1.0%, all rooms except A2-BR2 will meet the daylight requirements with 1.5m deep balconies (L/H=0.78). However, for different room configurations, mDF may decrease depending on the room plan, especially for rooms with one-sided windows.

3.6 Optimal façade design for classrooms

3.6.1 Daylighting

As mDF is not dependent on room orientation, results are grouped for cases with the same glazing VT and use of shading. All room variations without shading fulfil the mDF ≥ 2% requirement. Minimum and maximum values are presented in Table 17. For variations with shading, with VT 63.5% (south) and with standard materials mDF requirement is fulfilled by all variations with room depth 5m and by variations 5x6m, 7x6m and 9x6m (width x depth). With improved reflectance materials mDF is fulfilled by all variations with depth 5m, 6m, 7m, 8m except 6x8m and 8x8m, and 9m. For variations with VT 70.7% (east and west) and standard materials, mDF is fulfilled by all variations with room depth 5m, 6m, and 7m except cases 6x7m and 8x7m. With improved reflectance materials mDF is fulfilled by all variations except 6x9m.

Table 17. Minimum and maximum mDF values. (room size, width x depth).

	VT (%)	Standard materials		Improved reference materials	
		Min	Max	Min	Max
No shading	63.5	2.16%	3.93%	2.7%	4.91%
	(s, e, w)	6x9m	7x5m	6x9m	7x5m
	73.3	2.54%	4.61%	3.16%	5.64%
	(n)	6x9m	9x5m	6x9m	7x5m
Shading	63.5	1.42%	2.46%	1.74%	3.07%
	(s)	8x9m	7x5m	6x9m	9x5m
	70.7	1.56%	2.77%	1.98%	3.45%
	(e, w)	6x9m	7x5m	6x9m	9x5m

Code: s – south; e – east; w – west; n – north.

3.6.2 Temperature excess

Results of overheating simulations are presented and relation with mDF is analysed for room combinations only with standard materials. The mDF results are presented for different orientations due to different glazing VT and use of shading, and to analyse relation with overheating.

For south orientation, without shading all rooms exceed overheating limit and fulfil the mDF requirement (Figure 42). Classrooms with 5m depth are overheated up to 190Kh ($DH_{+25°C}$) and have a minimum mDF 2.16%. Adding shading helps to prevent all the rooms from overheating, but larger room depth reduces significantly daylighting. With the use of shading, $DH_{+25°C}$ is between 30Kh and 45Kh and mDF ranges between 1.42% and 2.46%.

East orientation results are more spread out. Without shading, for the room variations with depth 5m, 6m and 7m $DH_{+25°C}$ values are up to 175Kh, but all meet the daylight requirement with minimum mDF 2.16%, as is the case for south orientation. If for both east and west orientations shading is added and façade glass g-value increases from 0.35 to 0.42, room variations divide into three sectors (Figure 42). Rooms with 5m depth are overheated up to 120Kh ($DH_{+25°C}$) as horizontal shading can reduce only partially overheating of small depth rooms and present a minimum mDF of 2.5%.

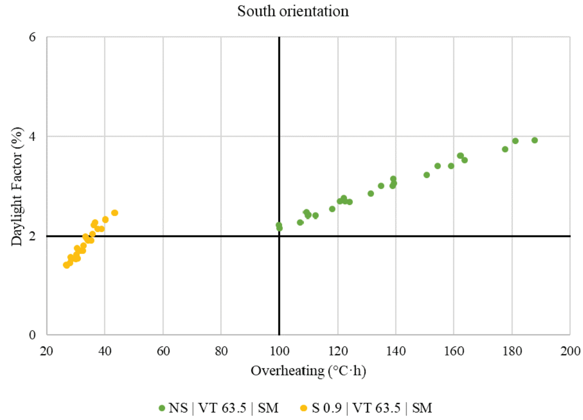


Figure 42. Mean daylight factor and temperature excess plot for south orientation. Upper-left sector variations fulfil daylighting (mDF>2%) and temperature excess ($DH_{+25°}$<100Kh) requirements. Code: NS – without shading; S – with shading; VT – visible transmittance of glazing; SM – standard materials.

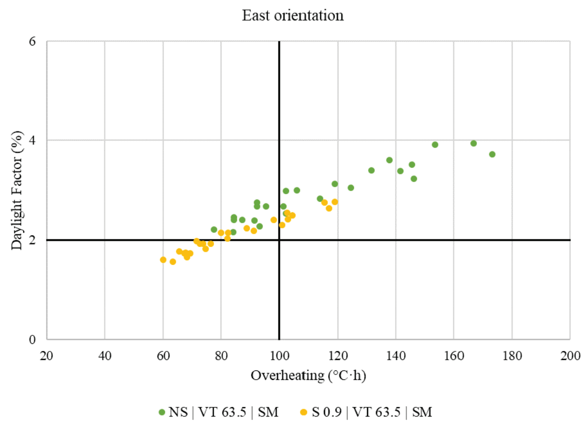


Figure 43. Mean daylight factor and temperature excess plot for east orientation. Upper-left sector variations fulfil daylighting (mDF>2%) and temperature excess ($DH_{+25°}$<100Kh) requirements. Code: NS – without shading; S – with shading; VT – visible transmittance of glazing; SM – standard materials.

North façade overheating is analysed only without shading as it is not necessary to block direct sunlight in north orientation. All the rooms meet both overheating and daylight requirements (Figure 44), as $DH_{+25°C}$ values are between 33Kh and 51Kh. Meanwhile, mDF decreases steadily from 4.61% to 2.54% as room depth increases. For north façade, higher glazing g-value 0.54 is used to allow more natural lighting entering classrooms.

For West façade without shading 5m depth room variations are overheating up to 117Kh (Figure 45), and all rooms meet the daylight requirement with mDF values between 2.16% and 3.93% (same of south and east). Adding horizontal shading and optimized g-value of 0.42, similarly to east, $DH_{+25°C}$ requirements are met, with the values between 47Kh and 82Kh. In these cases, mDF ranges between 1.56% and 2.77%.

Results show that overheating is not a problem for north orientations. Higher g-value and shading may be used to reduce the DH for other orientations. For south façade, overheating is avoided by adding horizontal shading, but extra shading may lead to less daylight for classrooms with larger depth. For both east and west orientations horizontal shading may help to some limits as simulation results are more outspread. Figure 43 and Figure 45 show that it is crucial for façade design to take both mDF and $DH_{+25°C}$ results into account.

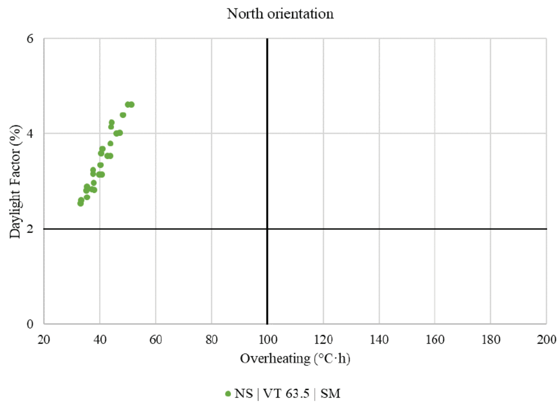


Figure 44. Mean daylight factor and temperature excess plot for north orientation. Upper-left sector variations fulfil daylighting (mDF>2%) and temperature excess ($DH_{+25°}$<100Kh) requirements. Code: NS – without shading; VT – visible transmittance of glazing; SM – standard materials.

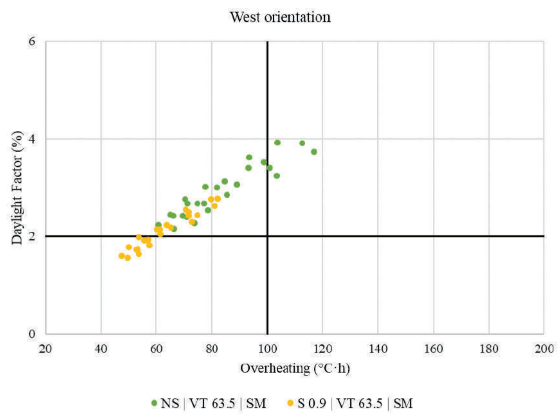


Figure 45. Mean daylight factor and temperature excess plot for west orientation. Upper-left sector variations fulfil daylighting (mDF>2%) and temperature excess ($DH_{+25°}$<100Kh) requirements. Code: NS – without shading; S – with shading; VT – visible transmittance of glazing; SM – standard materials.

3.6.3 Combined analysis of thermal comfort, daylighting and overheating

Results of temperature excess $DH_{+25°C}$ and daylight factor are presented for different orientations due to the different glazing g-value, VT and shading described in the methods section. For each orientation, a figure is composed, showing how rooms with different WFR and dimensions perform according to the requirements. Rooms are ordered by the WFR value, indoor climate class cumulative time is shown firstly, overheating secondly and daylight factor results thirdly. The colour-coded cumulative graph shows duration in percentages during which the hourly room temperature values stayed between the limits of a specific IC class, ranked from I (best) to IV (worst) according to the standard [9]. The $DH_{+25°C}$ and mDF values are marked as green squares, if both criteria are met and as red if one or both criteria do not meet the requirements. Room result figures are divided to left and right by shading use.

For east orientation (Figure 46) rooms without shading and with WFR over 0.23 are overheated and rooms with width of 5m also do not meet the overheating requirement. Same rooms gain 1 to 2% more time out of II IC class compared to rooms, which stay below 100Kh threshold. All the rooms without shading are well lighted as mDF is over 2%. It is seen, that as the WFR increases and floor plan has more width and less depth, classrooms are both more naturally lighted and overheated. If shading is added and glass g-value increases from 0.35 to 0.42, room air temperature hours in III and IV IC class decrease up to 3%. Most of the rooms are underneath the overheating requirement line, only half of the rooms meeting the daylight factor criteria. Only 6 rooms, compared to 10 in the initial situation, of 25 met both criteria.

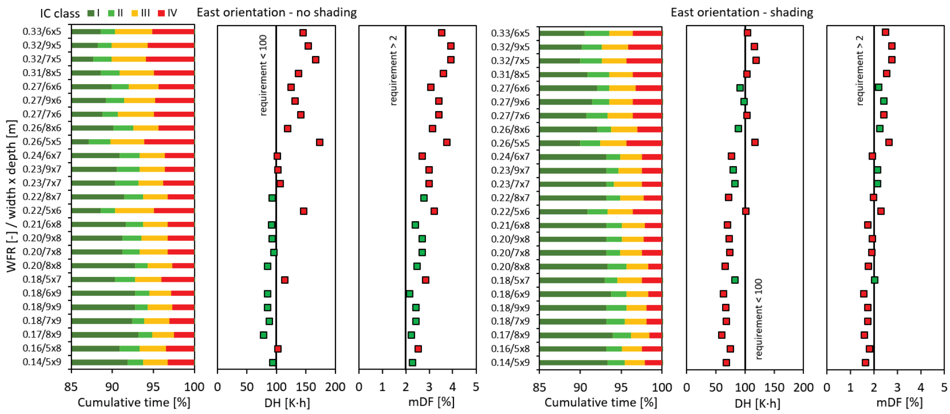


Figure 46. Simulation results for east oriented classrooms: indoor climate class (IC) cumulative time during the cooling period, temperature excess ($DH_{+25°C}$) and mean daylight factor (mDF) without (left) and with (right) shading.

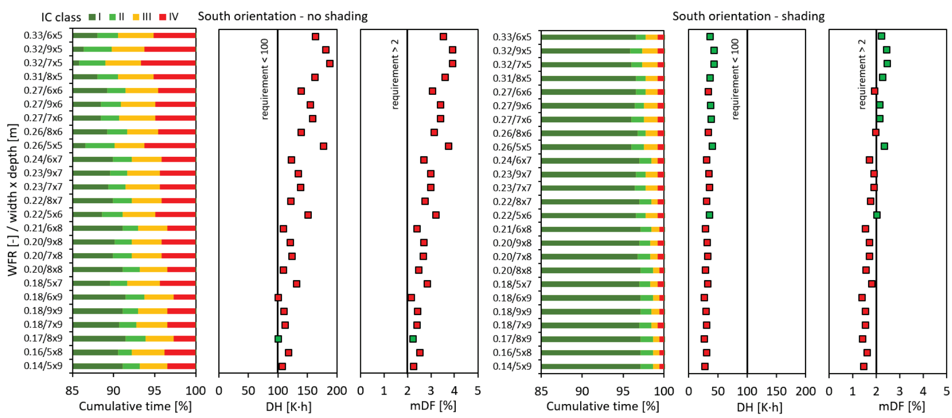


Figure 47 Simulation results for south-oriented classrooms: indoor climate class (IC) cumulative time during the cooling period, temperature excess ($DH_{+25°C}$) and mean daylight factor (mDF) without (left) and with (right) shading.

In south orientation (Figure 47) without shading, all rooms basically are overheated and properly naturally lit. Up to 10% of the time, air temperature in classrooms does not meet II IC class. After adding shading, only 2 to 3% of the time room air temperature is out of II IC class. While all the rooms now meet the overheating criteria, only 8 rooms of 25 have mDF over 2%.

For west orientation (Figure 48) 20 of 25 rooms meet both criteria without cooling, while room air temperature varies from 5 to 8% out of II IC class. Adding horizontal shading and optimized g-value of 0.42 similarly to the east orientation, all the rooms are below the overheating criteria, while 13 rooms with higher WFR do not meet daylight criteria. Classroom air temperatures IC classes for being out of II class also decreases between 3 to 5% of the time.

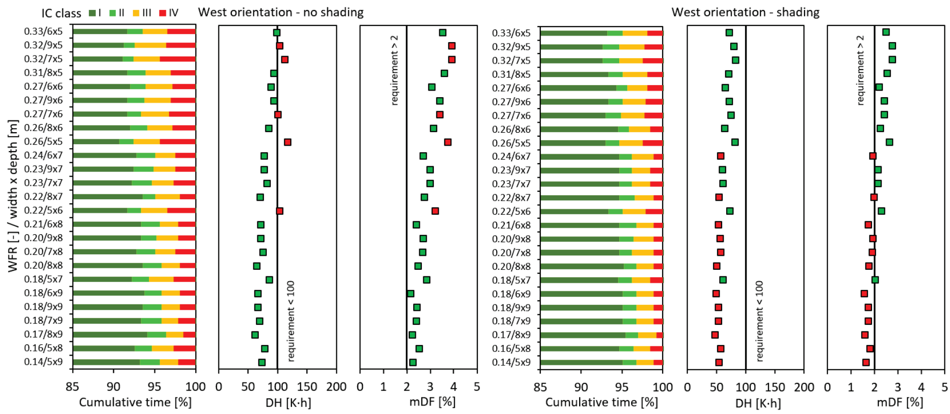


Figure 48 Simulation results for west oriented classrooms: indoor climate class (IC) cumulative time during cooling period, temperature excess ($DH_{+25°C}$) and mean daylight factor (mDF) without (left) and with (right) shading.

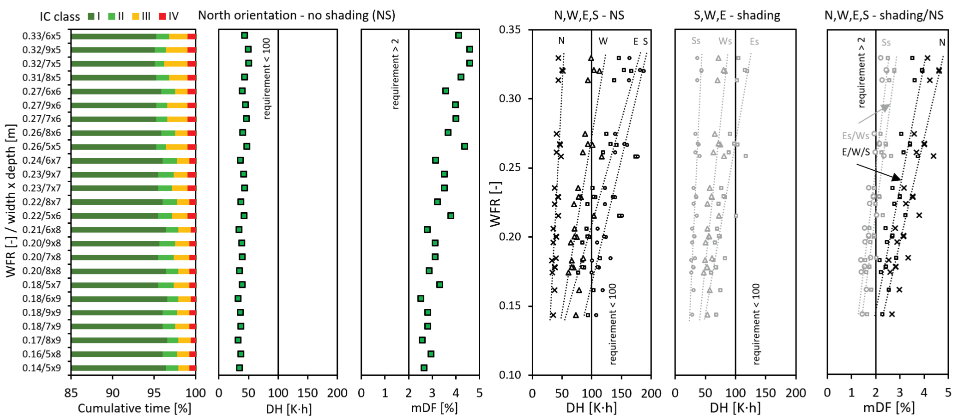


Figure 49 Simulation results for north-oriented classrooms: indoor climate class (IC) cumulative time during cooling period, temperature excess ($DH_{+25°C}$) and mean daylight factor (mDF) without shading (left) and for all facades, WFR correlation with DH and mDF (right).

As it is unnecessary to block direct sunlight on north façade (Figure 49), room results are presented only for the initial situation without shading. It is seen by the green squares that all the rooms meet both overheating and daylight factor criteria. Rooms with higher WFR have 1 to 2% more cumulative hours out of II IC class. Room $DH_{+25°C}$ values are more constant compared to higher mDF as the WFR increases.

For east, south and west orientations, rooms with a wider width and shorter depth dimensions received more daylight. For the north-oriented facade, all the analysed cases fulfilled the overheating and daylight requirements. IC class percentages indicate that room air temperature is mainly affected by internal gains of students, electrical equipment, lighting and supply air. Results are shaped less from the direct sunlight and as the WFR increases, more diffuse lighting enters the room. A similar distribution of results is seen on south façade with shading, but the balance gap between $DH_{+25°C}$ and mDF is clearly smaller for maintaining both criteria requirements. On the east and west façade results are more spread out, but still parallel as WFR increases. The room air temperature is less time out of II IC class for all south, east and west orientations if shading is added to the windows of the classrooms.

4 Conclusions

This thesis discusses existing overheating problems, assessment methodology and technical solutions to prevent overheating while ensuring sufficient daylight and sunlight availability in buildings without mechanical cooling systems. The study focuses on dwellings in apartment buildings and school building classrooms, to include samples from common residential and non-residential building types.

Indoor temperature measurement results taken from 16 apartment buildings during the summer of 2014 show that in several cases, hourly mean room temperatures did rise as high as +32°C and the majority of the dwellings were experiencing temperatures over +27°C for a remarkable portion of the measuring period, presenting clear evidence of overheating.

Summer thermal comfort compliance assessment of the studied buildings using dynamic computer simulations of 158 rooms from 25 buildings show that 17 out of 25 (68%) of the studied apartment buildings do not comply with the national requirements of Estonia. Evidently, the new overheating requirements were not taken into account in the design of all buildings. The main technical reasons for nonconformity were the use of large windows without shading and an insufficient area of operable windows. Therefore, it was found that the relatively new building code requirement was not fully established in practice. However, in these buildings where temperature simulations were conducted and passive measures were properly applied, the requirement was achievable without cooling. As an important outcome of the study, to mitigate the risk of overheating in new, planned residential buildings, it is recommended for authorities to pay more attention for EPC (random) checks and to check also within this process the availability and plausibility of overheating temperature simulation reports.

Design recommendations

Analysis of the measured and simulated results shows that shading balconies can have the largest effect on overheating risk reduction. As a rule of thumb, in south-oriented rooms, overhangs with length to window height ratio over 0.7 and side-fins, in case of west-oriented rooms, with the side-fin length to window width ratio also at least 0.7, were found sufficiently effective. However, the relatively small sample size should be taken into account. Secondly, the WWR·g-value under 0.2 showed in both measured and simulated cases lower temperature excess values. Lastly, it was found that the total openable area of windows should be at least 5%.

For a guideline, for selecting the 'critical rooms', that is, bedrooms or living rooms with the highest potential to encounter overheating, the defining parameters are found to be mainly a combination of different attributes, such as: south- and/or west-oriented windows, lack of external shading elements or insufficient dimensions of the shading, with WWR values over 0.4 or WWR·g-values over 0.2 and total windows' airing area lower than 5%.

In the north- and east-oriented rooms, significant correlations between shading, airing area or WWR was not found and no exceedance of temperature excess limit was registered. This can be explained with the low levels of direct solar radiation in north orientation and lower outdoor temperatures in the morning in east oriented rooms.

The study of classroom design shows that passive cooling methods, like decreasing window glass g-value and external shading decrease the amount of sunlight into the rooms, may cause poor conditions for natural lighting as a result. Therefore, both overheating and daylight parameters must be analysed jointly. Results show that as window-to-floor ratio increases, the room receives more daylight but also becomes more vulnerable to temperature rise and overheating. In the other hand, with increasing depth, overheating risk lowers and daylight level decreases. The conducted parametric study shows that horizontal shading is more helpful on the southern façade. Adding shading to eastern and western facades with modified window parameters, distribution of classrooms meeting both temperature excess, but the mean daylight factor decreases. The easiest balance between two criteria is on the north façade due to low amount of direct sunlight. Adding shading reduces the number of hours out of indoor climate class II, while temperature excess method illustrates more efficiently the intensity of overheating. In addition, temperature excess overheating method results correlates well with daylight result distribution. As school buildings are not used during summertime, it is possible to design classrooms to meet both overheating and daylighting requirements without the need for mechanical cooling systems. However, proper design requires skilful analysis of a suitable combination of room dimensions, window sizes, glazing parameters and shading options to meet both overheating and daylight requirements. On the basis of the findings, it is recommended to use more reliable climate-based simulations and metrics to assess more accurately daylight availability in building interiors.

Methodological findings

Thermal zoning effects on overheating risk prediction were analysed by comparing three thermal zoning methods: two multi-zone approaches, modelling the whole building or apartment, and a single-zone approach, modelling only one room. It was found that the average error increases with the decrease in model detail, thermal connections and airflow routes between neighbouring apartments and rooms. Although in some cases the change in statistical parameters seems low and acceptable in terms of overall indoor temperature prediction, the influence on excess temperature can be substantial, especially in small rooms with large glazing areas.

The analysis of the measurements and simulations reveal that the currently practiced single-zone simulation method, predicts well overheating risk. In the rooms where overheating was measured, single-zone model provided the best agreement, indicating that the open doors assumption of the multi-zone model is always not valid in practice. However, as being sensitive for overheating risk estimation, for more accurate predictions, the single-zone method is typically overestimating overheating in the real situation, because it is not accounting the thermal dynamics of the building, heat dissipation between the zones, as well as limitations in accounting e.g. cross-ventilation. Therefore, the apartment based multi-zone method gave more realistic results, with little differences to the whole building approach, and can be suggested as an alternative method for more accurate simulations.

It needs to be emphasized that the Estonian single-zone method relies on ventilative cooling through buoyancy-driven window airing, and the fixed window opening position, defined in the regulation, gives sometimes room for interpretations in the design phase and is challenging for simulation tools as well. However, window airing seems to be compensating the oversensitivity of the single-zone model resulting in solid performance according to the measurements of this study.

Although overheating assessment by simulation is required by the state regulations the occupants might be interested in temperature measurement-based assessment Using the proposed measurement-based method, it is relatively easy to pre-assess an apartment or living space with only temperature measurements, without having to conduct simulations to prove the existence of overheating problems. Although the buildings analysed in the current study represent well current construction practice, further research with a larger sample representing a larger variety of buildings could be recommended.

By analysing the conflicts between overheating prevention regulations and standards requiring daylighting and insolation, it was found that the mean daylight factor correlates strongly with overheating calculation results in terms of temperature excess and would be preferable to insolation duration metric. Based on the studies of both residential buildings and classroom design, a revision of the actual Estonian daylight standard is recommended.

The analysis shows that in case of Estonia, the minimum number of hours during which a room should receive direct sunlight should be proven for a reference day instead of a period of days, as required by the national standard for daylighting in buildings. In addition, the requirements should allow more flexibility, especially for difficult cases, either shorter insolation duration periods or qualitative class-based assessment. It may be reasonable to establish rules for calculating insolation duration for rooms with balconies. During hot summer periods, allowing direct sunlight into rooms is not recommended, as it directly increases the risk of overheating. In most cases, assessing the mean daylight factor values instead of insolation analysis would be sufficient and preferable to assess daylighting and allow reduce overheating risk. In special occasions and more difficult cases, insolation analysis may prove necessary. In these cases, it is recommended to apply insolation requirements only for spring months, e.g. for April, with lower elevation angles and azimuth angle averages equal to or less than one hour compared to summer months.

Future work

The current work focused mainly on the methodology based on the standardised national regulations which account for deterministic building use and occupant behaviour. Future work should include aspects of variable behaviour, for example, stochastic occupant models to account for internal heat loads and occupants' presence.

It is important to assess the occupants' perception of thermal comfort, limit temperatures and overheating. Also, regarding occupant behaviour, the use of ventilative cooling via window opening habits should be investigated to analyse the frequency and temperatures by which the windows are opened and closed. A thorough field study including questionnaire should be conducted to assess these topics.

Another important aspect is analysing buildings under different changes in weather conditions due to climate change. The buildings designed and constructed today face the problems of increasing frequency and severity of weather extremes in the future. As the Test Reference Year (TRY) is based on climate data from several decades ago (1970-2000) and aimed mainly for building energy performance estimation, future work should provide a Design Summer Year (DSY) or a set of DSYs with different severity, accounting for climate change projections and probability of heatwaves, to be used for cooling energy calculations and overheating assessment for future buildings. This could provide insight to what extent passive measures can be effective to prevent buildings in the future from overheating.

We analysed only preliminary façade designs of typical classrooms using standardised methodology for overheating risk and daylighting assessment. The design-based estimations should be compared with the real performance by conducting a field study to investigate classroom conditions in terms of overheating, visual and thermal comfort in newly renovated and new school buildings built to the nZEB standards.

As building simulation tools are improved over time, several software solutions today allow to carry out multi-objective optimisation of different parameters simultaneously. Such optimisation methods and strategies should be applied to analyse the effects of passive design measures on the whole-year performance of buildings, including energy consumption for heating and lighting as well as specific variables regarding daylighting quality.

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Abstract

Overheating Prevention and Daylighting in Buildings without Mechanical Cooling

In modern low-energy buildings without mechanical cooling systems with highly insulated airtight envelopes and often large glazed surfaces, overheating is an increasingly common problem, even in temperate and cold climate countries. The current thesis aims to address the problems of overheating assessment and prevention in residential and non-residential buildings with a focus on passive measures and daylighting. Indoor temperature measurement results taken from 16 newly constructed apartment buildings show clear evidence of overheating. Compliance assessment of new buildings show that 68% did not meet the requirements for overheating prevention, indicating that the relatively new building code requirement was not fully established in practice. The main reasons for nonconformity were the use of large windows without shading and an insufficient area of operable windows. We used indoor temperature measurements and dynamic simulations to analyse the main causes of overheating in dwellings and defined the main parameters for 'critical' rooms which would most likely encounter overheating problems. As a result, passive solutions to prevent overheating were possible to generalize with a new formula including window to wall ratio and solar factor of shadings and glazing. As a set of rules of thumb were given for overhang length and window height ratio for south-oriented rooms, and side-fins length to window width ratio for west-oriented rooms. Simulation models with different thermal zoning levels were studied: single-zone models, multi-zone apartment models and multi-zone whole building models. By analysing the measurements and simulations it was shown that the currently practised single-zone simulation method, predicts well overheating risk. Analysis of the overheating assessment methodology showed that multi-zone method results were in closer agreement between measured and simulated temperatures whereas the currently practised single-zone method proved to be a safe side conservative method. Analyses also produced a new formula which allows to scale the measured indoor temperatures and temperature excess to the value applying with test reference year which is used in compliance assessment methodology. Sunlight and daylight analyses of the shading effect of balconies showed a conflict between insolation and overheating requirements and provided evidence that insolation analyses are sufficient for fixed day instead of a long time period. Holistic classroom façade analysis showed that passive design is possible in Estonian climate and which technical solutions are needed in order to meet overheating, daylight and sunlight criteria.

Lühikokkuvõte
Ülekuumenemise vältimine ja loomuliku valguse tagamine mehaanilise jahutuseta hoonetes

Kaasaegsetes madala energiatarbega hoonetes, kus pole mehaanilisi jahutussüsteeme, millel on õhutihedad, madala soojusläbivusega välispiirded ning sageli suured klaaspinnad, on ülekuumenemine üha tavalisem probleem ning seda ka külma kliimaga riikides. Käesoleva töö eesmärk on lahendada elamute ja mitteeluhoonete ülekuumenemise hindamise ja ennetamise probleeme, keskendudes passiivsetele meetmetele ja loomuliku valguse tagamisele. Korterelamutes teostatud sisetemperatuuri mõõtmistulemused näitasid selgeid ülekuumenemise probleeme. Hoonete analüüsil selgus, et 68% hoonetest ei vasta suvise ruumitemperatuuri nõuetele, viidates sellele, et uued nõuded polnud praktikas veel täielikult realiseerunud. Peamised mittevastavuse põhjused olid suured varjestamata aknad ja ebapiisava suurusega tuulutuseks avatavad aknad. Eluruumide ülekuumenemise peamiste põhjuste analüüsimiseks kasutati sisetemperatuuri mõõtmisandmeid ja dünaamilisi simulatsioone, mille abil määratleti kõrge ülekuumenemise riskiga „kriitiliste" ruumide peamised parameetrid. Selle tulemusel oli võimalik anda ülekuumenemise vältimiseks toimivate passiivsete lahenduste seosed akna ja seina suhte ning akna klaaspaketi päikesefaktori kohta. Lõuna-suunaliste ruumide jaoks leiti rusikareeglid horisontaalse varjestuse pikkuse ja akna kõrguse suhte jaoks ning läänesuunaliste ruumide korral vertikaalse külgvarjestuse pikkuse ja akna laiuse suhte jaoks. Lisaks uuriti simulatsioonimudeleid erineva tsoneerimise tasemega: ühetsoonilised mudelid, mitmetsoonilised korterimudelid ja mitmetsoonilised terve hoone mudelid. Mõõtmiste ja simulatsioonide analüüsist järeldus, et praktikas kasutusel olev ühetsoonilise simulatsioonimudeli meetod ennustab piisavlat hästi ülekuumenemise riski. Ülekuumenemise hindamise metoodika analüüs näitas, et mitmetsoonilise meetodi tulemused olid mõõdetud ja simuleeritud temperatuuride vahel tihedamalt kooskõlas, samas kui ühetsooniline meetod on konservatiivsem ja robustsem. Tulemuste põhjal töötati välja metoodika, mis võimaldab sisetemperatuuri mõõtmistulemuste põhjal anda ligikaudselt hinnata hoone vastavust suvise ruumitemperatuuri nõudele. Päikese- ja päevavalguse analüüs rõdude varjestamise efekti osas näitas vastuolu insolatsiooni ja ülekuumenemise vältimise nõuete vahel. Tulemused näitavad, et ülekuumenemise nõuse tagamiseks tuleks insolatsioonianalüüs pika ajaperioodi asemel teostada kindla päeva kohta. Klassiruumide fassaadianalüüs näitas, et passiivne disain on Eesti kliimas võimalik ja milliseid tehnilisi lahendusi on vaja ülekuumenemise ja päevavalguse kriteeriumide täitmiseks.

Appendix

Publication I

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Summer thermal comfort: compliance assessment and overheating prevention in new apartment buildings in Estonia

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This study analyses which building parameters contribute the most to overheating in dwellings and which properties will make a room 'critical', to be chosen for compliance assessment procedure through temperature simulation, as required in Estonia for new residential buildings. Indoor temperature measurements, conducted in 18 apartments from 16 apartment buildings, show clear evidence of overheating. Compliance assessment of 25 new buildings were conducted using IDA-ICE software. The analysed sample consisted of typical multi-storeyed buildings with mainly massive concrete structures. From the simulated buildings, 68% did not meet the requirements, showing that this relatively new building code requirement was not fully established in practice. Results of the analysis indicate that the requirement in apartment buildings is achievable without cooling, if passive measures are properly applied. Recommendations are given to designers, as well as policy-makers, to improve the situation in the residential building sector.

Keywords: compliance; building simulation; field study; summer thermal comfort; overheating prevention; IDA-ICE

1. Introduction

With the goals to cut Europe's primary energy consumption by 20%, the Energy Performance of Buildings Directive (EPBD) 2010/31/EU (EU 2010) has been launched to reduce the energy consumption of building sector, by obligating Member States to impose requirements for buildings energy efficiency. As one of the priorities, it is stated that even with lower energy usage, healthy indoor climate must be provided, including summer thermal comfort. New building technologies, regarding the building envelope structure and design, together with international architectural styles, with little distinction anywhere in the World – namely the use and abuse of poorly shaded glazed façades – have caused a generalized tendency for overheating (Maldonado 2005). This is especially the case in new residential buildings (Chvatal and Corvacho 2009) with improved air tightness, higher levels of insulation, large glazing areas and lack of mechanical cooling (Beizaee, Lomas, and Firth 2013).

With the introduction and development of building simulation tools, the use of thermal modelling has continuously grown in the last decades and has gained much importance as a part of the building design phase. Simulation-based assessment of planned buildings energy consumption has become a vital part of Standards and Building codes. With the help of the new Directive, some progress, regarding implementation of the procedures for providing summer thermal comfort assessment strategies, has been made. However, as the problems with summer overheating in colder climate regions have not been an issue before or have been simply ignored in the Building regulations in most countries, the know-how in preventing and addressing these problems, as well as adapting to the new regulations, is proven insufficient amongst architects, designers and engineers.

1.1. Thermal comfort, overheating assessment and prevention

Fanger (1970) has defined 'Thermal comfort' as the combined effects of six fundamental factors: temperature, relative humidity, thermal radiation, air relative velocity, metabolic rate and clothing insulation. Some of these parameters are relatively easy to assess, maintain and measure (e.g. temperature); for others (e.g. metabolic rate, clothing), it may prove difficult. The addition of the variability in individual perception of comfort makes defining any specific threshold for overheating, in the context of buildings, complex and challenging. There have been various indices and scales (Epstein and Moran 2006; Hamdy and Hensen 2015) used to measure thermal comfort and heat stress. Also, a number of methods have been developed to assess the risk of overheating (Carlucci and Pagliano 2012). For example, based on the concept

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of adaptive, as opposed to Fanger's static thermal comfort, the European standard EN 15251 (CEN 2007) gives a maximum allowable difference from comfort temperature. On the other hand, the CIBSE Environmental Design Guide A (CIBSE 2015) suggests a benchmark approach be used, where the summertime thermal performance of the building is measured against a temperature that should not be exceeded for a defined number of hours or percentage of the occupied hours. It should be noted that these single-temperature exceedance threshold criteria are usually developed for a specific population or geographic location and may not be applicable to other regions with different climatic conditions. As indoor temperature is easy to comprehend and measure, many other overheating criteria are based on the room temperature duration over a threshold value in a given time.

In terms of passive cooling solutions, a framework of three steps can be stated: heat gains prevention, modulation of the heat gains and heat dissipation. In a recent overview on thermal comfort studies (Halawa, van Hoof, and Soebarto 2014), researchers have emphasized the importance of mean radiant temperature on occupants' thermal comfort – blocking the direct solar radiation has the potential to significantly improve thermal comfort by means of improving the operative temperature and radiant asymmetry (Bessoudo et al. 2010) and also reduce the risk of overheating. Kim et al. (2012) have assessed the thermal performance of external shading devices and found that from the conventional shading devices, overhangs or lightshelfs can have the highest effect on cooling load reduction. In their studies, Charde and Gupta (2013a, 2013b) and Cho, Yoo, and Kim (2014) have shown that with the combination of proper design of building elements and static shades, it is possible to assure comfortable indoor air temperature throughout the year and to avoid overheating in summer. According to Balogun, Morakinyo, and Adegun (2014), best ways to avoid high indoor temperatures is to use façade shading elements and sufficient ventilation. They also state that foliage shading – especially higher trees – can have substantial effect on indoor temperature.

During the last five years, there have been several large-scale studies carried out in Estonia, with the focus on the technical condition and indoor climate of the residential building stock (Kalamees et al. 2012). Although the majority of the studied buildings were built before 1990s, a considerable sample of newer buildings with construction year between 1990 and 2010 was also included. It was found that indoor temperatures exceed the criterion of weighted excess degree-hours above +27°C in 63% of the studied dwellings. Maivel, Kurnitski, and Kalamees (2014) studied summer thermal comfort-related problems in both old and new apartment buildings in Estonia and also found that overheating is most probable in new buildings. Problems with high indoor temperatures have been reported also in other cold climate regions. In Sweden, occupants in retrofitted (Liu, Rohdin, and Moshfegh 2015) and low-energy buildings (Rohdin, Molin, and Moshfegh 2014) have complaints over high temperatures in the summer.

1.2. *Requirements in Estonia*

To assess the levels of thermal comfort in dwellings, a new compliance regulation has been launched in Estonia – 'Minimum requirements of Energy Performance' (GOV 2012b) – to meet its obligations after the adoption of the EPBD directive (EU 2010) that required the Member States to provide a standard assessment procedure for evaluating the likelihood of overheating, during the everyday performance of new buildings and major building renovations. The new regulation states that all buildings, which have acquired a construction permit after the year 2009, are required to comply with this regulation, which also regulates the verification of summer thermal comfort compliance in buildings. The compliance verification procedure is given in detail in regulation No. 63, 'Methodology for calculating the energy performance of buildings' (GOV 2012a).

The main objectives of this study were to:

- Get an overview of the current situation regarding summertime indoor temperatures in newly built apartment buildings;
- Assess the compliance of the buildings through computer simulations;
- Identify the parameters that define a 'critical' room most likely to counter overheating;
- Identify passive measures used in practice that effectively reduce the risk of overheating.

To estimate overheating risk in recently built apartments, we have taken indoor temperature measurements in 18 living rooms and bedrooms from 16 different apartment buildings during the summer period of 2014. For summer thermal comfort compliance assessment of the studied buildings, we have simulated indoor temperatures in chosen rooms most likely to counter overheating problems. We have used indoor environment and energy simulation software IDA-Indoor Climate and Energy (ICE) and climatic data from Estonian Test Reference Year (TRY), with input parameters for internal heat loads and usage profiles, as defined in Estonian regulation No. 63 (GOV 2012a). In total, 158 rooms from 25 buildings were simulated. The results from measurements and simulations were used to identify the 'critical room' defining parameters and to find out, which design measures can reduce the risk of overheating.

2. Methods

In this chapter, description of the methods, climate data, studied buildings, conducted measurements and simulations are given. The compliance verification of buildings was assessed according to the requirements described in Estonian regulations No. 68, 'Minimum requirements for energy performance' (GOV 2012b) and No. 63, 'Methodology for calculating the energy performance of buildings' (GOV 2012a). According to the methodology, overheating risk assessment is required for 'critical rooms', that is, living rooms and bedrooms, which have the greatest potential to counter high temperatures. When assessing compliance of a building, every single living room and bedroom is required to comply. If the requirement is not met even in one of the rooms, the whole building is considered as non-compliant and measures to prevent over-the-limit temperature excess have to be applied.

Several large-scale studies have indicated that there are no distinct differences in average mean temperatures during daytime in living rooms and during night-time in bedrooms (Lomas and Kane 2013; Maivel, Kurnitski, and Kalamees 2014), thus using the same criteria on both room types seems fairly adequate when using a static thermal comfort criterion. However, there are differences regarding typical occupied hours in living rooms and bedrooms, as well as differences in occupant clothing and activity levels, which are accounted in, for example, the CIBSE Guide A adaptive comfort criteria (CIBSE 2015), which gives different approaches for living rooms and bedrooms. It should be also noted, that as guidelines, standards and regulations deal only with spaces that are assumed by default as frequently used, such as bedrooms and living rooms, there is no clear difference regarding overheating issues in other rooms, for example, kitchens, dining rooms and so on.

According to Estonian regulations, to quantify the overheating risk, indoor temperature excess (DH) in degree-hours (Kh) is used, which is calculated from simulated or measured hourly mean room temperature values as

$$\mathrm{DH}_{t_b} = \sum_{i=1}^{j} (t_i - t_b)^+, \tag{1}$$

where DH_{t_b} is the temperature excess in degree-hours over the base temperature t_b (°C), t_i is the hourly mean room temperature and j is the total number of hours during the given period. The '$+$' sign means that only positive values are summed.

For residential buildings, the requirement is defined as hourly mean indoor temperature excess maximum limit of 150 Kh over a base temperature of $t_b = +27$°C during the summertime period from 1 June to 31 August, thus $j = 2208$. The Equation (1) can be given as (GOV 2012a)

$$\mathrm{DH}_{+27^\circ\mathrm{C}} = \sum_{i=1}^{2208} (t_i - 27)^+. \tag{2}$$

The calculations include occupied hours only, which, for residential buildings, is the full period, including night-time. For the compliance assessment, a detailed procedure and requirements for calculation software are described in regulation No. 63 'Methodology for calculating the energy performance of buildings' (GOV 2012a). Indoor temperature simulations are needed for typical living rooms and bedrooms in the building that could experience overheating. The verification is to be conducted considering rooms as single zones and by using dynamic simulation software that meets the requirements described in GOV (2012b). One of the most important differences between modelling residential and non-residential buildings is the use of ventilative cooling through the opening of windows, which is not taken into account in non-residential buildings. In residential buildings, the opening of windows to the airing position – instead of fully opened window – is especially stressed in the regulation and the air change driven by the difference between outdoor and indoor temperature is taken into account – wind-driven air change is not allowed to be simulated, to enable the use of a wider list of simulation software and to avoid large differences in calculation results (GOV 2012a).

2.1. *Climate data*

Estonia is located in the northern part of the temperate climate zone. The climate can be described as typical European continental influenced climate with warm, dry summers. The average annual temperature is $+5.2$°C and average temperatures during the warmest month (July) range from $+16.3$°C on the Baltic islands to $+18.1$°C inland in July (Estonian Weather Service 2015). The probability that daily maximum temperatures exceed $+30$°C is highest in July. In the inland regions of Estonia, such temperatures occur nearly every year and in coastal areas every third year (Keevallik and Vint 2015). Climate change scenarios for Estonia estimate an increase in the annual mean temperature of 3–4 K (Mändla 2016) and around 5 days annually with temperatures above $+30$°C (Beniston et al. 2007) for the end of the twenty-first century, indicating high probability of heatwaves.

When assessing building performance regarding both energy consumption and summer thermal comfort assessment calculations, according to the ordinance No. 68 (GOV 2012a), the simulations are required to perform regardless of the location of the building using the TRY (Kalamees and Kurnitski 2006). The TRY is constructed by using different months from three decades (1970–2000) of climatic data that best describe Estonian climate. It contains hourly mean data of outdoor temperature, relative humidity, wind speeds and solar radiation.

The indoor temperature measurements in dwellings were performed in the summer of 2014. Compared to outdoor temperatures from TRY (Figure 1, left), the 2014 summer was relatively warm, with two distinctive heat waves with hourly mean outdoor temperatures reaching

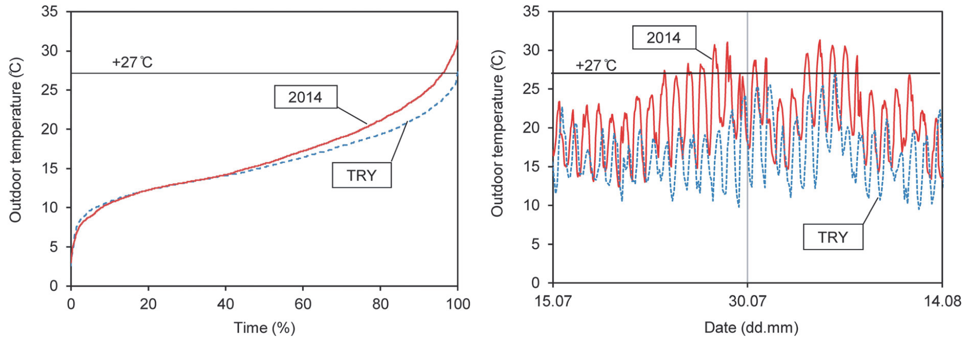

Figure 1. Hourly mean outdoor temperature duration curves for summertime period from 1 July to 31 August (left) and heat waves in June and August 2014 (right). Data from TRY (Kalamees and Kurnitski 2006) and weather station measurements (Estonian Weather Service 2015, EMHI).

higher than $+30°C$ (Figure 1, right). The outdoor temperature excess $DH_{+27°C}$ in 2014 was 157.3 Kh, whereas in case of TRY, the temperature excess $DH_{+27°C}$ is 0.5 Kh (Figure 1, left).

2.2. *Description of the studied buildings*

The apartment buildings pertaining to this study were selected randomly, using the criterion of building permit acquisition year 2009 and later, to define each building as ‘new’, on the basis of the regulations entry into operation. The buildings varied in terms of architectural design, envelope construction type, number of glazed surfaces and window types, geometry, height, location, orientation and other factors. Most of the buildings were designed with precast or monolithic concrete structures with more than four floors above ground. Table 1 gives an overview of the main building parameters used as input data for simulations. The data were acquired from the buildings design documentation and Energy Performance Certificates (EPCs). An example of a typical apartment architectural plan and buildings cross-section is shown in Figure 2. The thermal transmittances for the envelope parts as presented in Table 1 were calculated in the simulation software by defining the material layers defined also in the design documentation. The room sizes in apartments varied in large numbers – the average floor area of living rooms was 28.9 m^2 with a standard deviation of 10.4 m^2, for bedrooms, the average floor area was 12.5 m^2 and a standard deviation of 3.3 m^2.

The buildings in this study used either a central mechanical exhaust ventilation system or a decentralized mechanical supply-exhaust system with apartment-based air handling units – both commonly used in Estonian residential buildings. In case of the mechanical exhaust systems, outdoor air was supplied to the dwellings through fresh air valves, located in external walls, or through window integrated air valves.

As of passive cooling techniques, besides ventilative cooling, only one of the buildings had glazing with a low g-value (0.4) for south–west-oriented façade; one of the studied apartments had internal venetian blinds between the windowpanes, and most commonly, the use of balconies as shading elements was identified. Other intentional measures, such as external window shading, were not registered. Also, no active cooling measures in the buildings were registered – a common practice in Estonian apartment buildings.

The thermal transmittances of the buildings’ envelope were found to be between 0.15 and 0.25 $W\,m^{-2}\,K^{-1}$ for external walls, 0.09 and 0.17 $W\,m^{-2}\,K^{-1}$ for roofs and 0.60 and 1.65 $W\,m^{-2}\,K^{-1}$ for windows, with solar factors varying from 0.40 to 0.71.

2.3. *Measurements*

Indoor temperature measurements were carried out during the period from 1 July to 31 August in 22 apartments in 16 different apartment buildings. The chosen apartments were assumed to have the highest risk of overheating, for example, with south or west orientation, located on higher floors, relatively large glazing areas etc. For measurements, previously calibrated data logging Onset Hobo U12-012 devices (ONSET 2015) were used. The temperature measuring range of the devices is from -20 to $+70°C$, with accuracy ± 0.35 K, and relative humidity from 5% to 95%, with accuracy $\pm 2.5\%$ of full scale output. The data loggers were placed in the occupied zone of the rooms so that they would not be affected by direct sunlight, ventilation airflows, heat-generating equipment and so on. The placement height of the loggers was between 1.0 and 1.6 m.

2.4. *Simulations*

In order to determine overheating risk of dwellings and for assessing the apartment buildings’ compliance with

Table 1. Specification and input data used in simulations (data collected from building design documentation and EPCs).

Building no	Building structure type	Thermal transmittance of envelope part, W m^{-2} K^{-1} Ext. wall	Roof	Windows	Windows g-value, -	Ventilation system type	Building height, m	Floors above ground	Infiltration, l s^{-1} m^{-2} ext. surf.	Passive cooling elements
B1	Wood-frame	0.21	0.16	1.06	0.68	Mech. exhaust	10.6	4	0.042	Balconies
B2	Wood-frame	0.17	0.14	0.63	0.55	Mech. supply-exhaust	11.0	4	0.042	–
B3	L/W concrete blocks	0.16	0.14	1.10	0.69	Mech. exhaust	12.0	4	0.042	–
B4	Concrete	0.15	0.17	1.14	0.71	Mech. exhaust	26.5	10	0.056	–
B5	L/W concrete blocks	0.18	0.12	1.10	0.65	Mech. supply-exhaust	19.3	6	0.056	Balconies
B6	Concrete	0.24	0.14	1.00	0.40	Mech. supply-exhaust	18.5	6	0.056	Balconies
B7	Precast concrete	0.23	0.12	1.01	0.55	Mech. exhaust	14.6	5	0.056	Balconies/ Shading trees
B8	Precast concrete	0.17	0.09	0.60	0.48	Mech. exhaust	21.0	6	0.056	Balconies
B9	Precast concrete	0.17	0.14	0.89	0.60	Mech. exhaust	14.0	4	0.042	Balconies
B10	Precast concrete	0.23	0.16	1.20	0.63	Mech. supply-exhaust	24.9	7	0.056	Cross ventilation
B11	Concrete	0.16	0.14	1.10	0.69	Mech. exhaust	21.5	6	0.056	–
B12	Concrete	0.22	0.15	1.00	0.70	Mech. supply-exhaust	17.0	5	0.056	–
B13	Precast concrete	0.23	0.16	1.10	0.67	Mech. supply-exhaust	25.1	7	0.056	–
B14	Wood-frame	0.25	0.17	1.40	0.70	Mech. exhaust	8.3	2	0.035	Shading trees/ Cross ventilation
B15	Precast concrete	0.21	0.12	1.65	0.63	Mech. supply-exhaust	12.0	3	0.042	Balconies
B16	Precast concrete	0.21	0.12	1.65	0.63	Mech. supply-exhaust	12.0	3	0.042	Balconies
B17	Concrete	0.23	0.13	1.01	0.55	Mech. exhaust	16.0	5	0.056	–
B18	Precast concrete	0.18	0.11	1.30	0.63	Mech. supply-exhaust	10.9	3	0.042	Balconies
B19	Precast concrete	0.18	0.11	1.30	0.63	Mech. supply-exhaust	13.9	4	0.042	Balconies/ Cross ventilation
B20	Precast concrete	0.19	0.09	0.80	0.50	Mech. supply-exhaust	24.7	9	0.056	Balconies/ Cross ventilation
B21	H/W concrete blocks	0.18	0.14	0.92	0.54	Mech. supply-exhaust	7.2	2	0.035	Cross ventilation
B22	L/W concrete blocks	0.16	0.13	1.10	0.60	Mech. supply-exhaust	7.0	2	0.035	Shading trees/ Balconies
B23	Precast concrete	0.17	0.14	1.00	0.55	Mech. exhaust	10.3	3	0.042	Balconies/ Cross ventilation
B24	Precast concrete	0.18	0.11	1.10	0.58	Mech. supply-exhaust	21.2	6	0.056	Balconies
B25	L/W concrete blocks	0.16	0.12	1.04	0.56	Mech. exhaust	8.7	2	0.035	Balconies

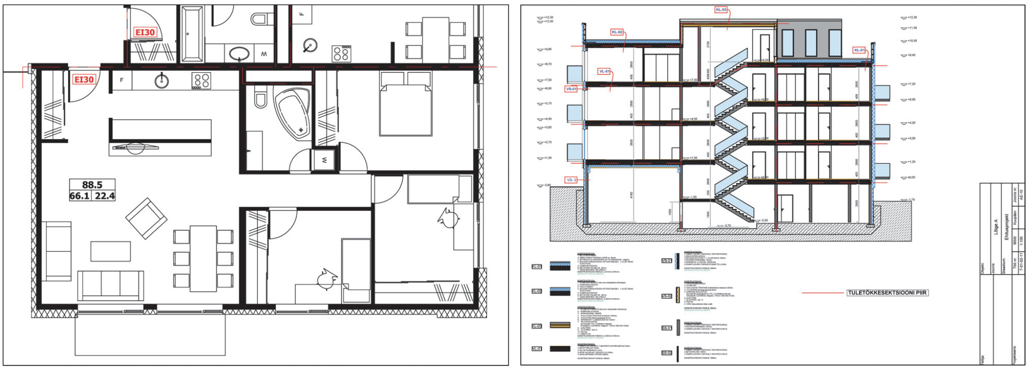

Figure 2. Example of a studied buildings architectural drawings: apartment plan (left) and building cross-section with specifications of the building structures (right).

summer thermal comfort, room temperature simulations are required (GOV 2012b). In this study, we used indoor climate and energy simulation software, IDA-ICE version 4.6.1 (EQUA 2014). This tool allows detailed and dynamic whole-year multi-zone building simulations of indoor climate, energy consumption and building systems performance. The software has been validated according to European Standard CEN 13791 'Thermal Performance of Buildings – Calculation of Internal Temperatures of a Room in summer without Mechanical Cooling – General Criteria and Validation Procedures' defined test cases (Kropf and Zweifel 2002).

Input data for the buildings in question, including building site surroundings, architecture, floor plans, and specifications for walls, roofs and windows were acquired from the design documentation of the buildings, the Estonian Registry of Buildings database (2014) and the Estonian Land Board web map (2014).

The simulations were made according to the methodology described in GOV (2012a). The simulation models use a single-zone method, meaning that only selected rooms are modelled individually with no connections to other rooms (Figure 3). In case of residential buildings, at least two 'critical' rooms are required to simulate, one bedroom and one living room, which have the biggest potential to score high temperatures, for example, south or west orientation, higher floor location, and relatively large glazed surfaces. The selection of these rooms is up to the energy efficiency specialist, designer or HVAC engineer responsible for the calculations (Figure 3).

The thermal properties of external boundaries were calculated automatically in IDA-ICE by defining the material layers with appropriate parameter values for each layer, which included properties for thermal conductivity, specific heat and density for accurate calculation thermal mass of the building and heat fluxes through the structures. The overview of the material propertied used is given in

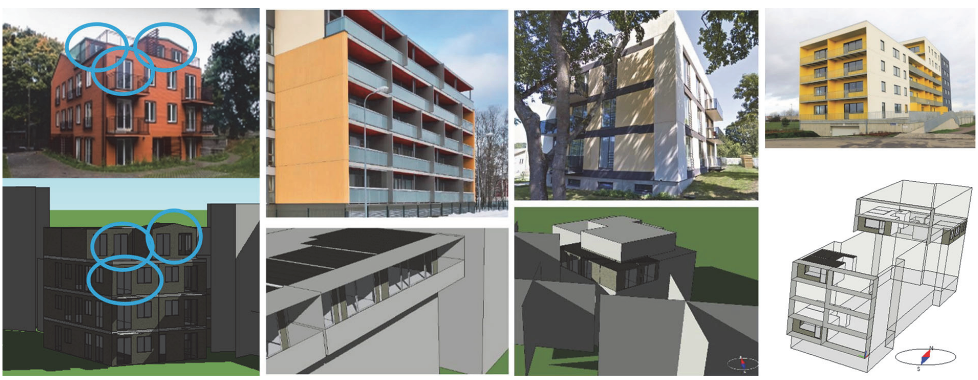

Figure 3. Example of modelled buildings with shading elements and selection of 'critical' rooms, which have highest potential to counter overheating. Photos (top) and simulation models (bottom).

Table 2. Overview of the material properties used in the thermal transmittance calculations of building envelope structures.

Material	Thermal conductivity, $W\,m^{-1}\,K^{-1}$	Specific heat capacity, $J\,kg^{-1}\,K^{-1}$	Density, $kg\,m^{-3}$
Concrete	2.00	1000	2400
Gypsum board	0.5	1000	900
Mineral wool	0.04	850	60
Oriented strand board	0.10	1880	555
Wood	0.14	2300	500
Expanded polystyrene	0.04	850	15
Concrete block	1.19	880	2100

Table 2. Solar heat gain coefficients of windows, if not available in design documentation, were calculated using detailed window model with glazing properties calculation tool in IDA-ICE. Overall values used in buildings simulations are shown in Table 1.

Trees close to the buildings that would cast shadows were modelled as crossing vertical rectangular planes (Figure 3). The shading effect of foliage was estimated as transparency factor between 0.2 and 0.3 (with 1.0 being fully transparent) (Heisler 1986).

Infiltration for the buildings was calculated using the following equation (GOV 2012a):

$$q_i = q_{50} \times A/(3.6 \times z), \tag{3}$$

where q_{50} is the building air permeability at 50 Pa pressure difference, $m^3\,h^{-1}\,m^{-2}$; A is the total area of building envelope, m^2 and z is the building height factor: 35 for one, 24 for two, 20 for three and four and 15 for five and higher story buildings. For all of the cases, building air permeability value of 3.0 $m^3\,h^{-1}\,m^{-2}$ was used, as is required for calculations in case of new buildings, according to GOV (2012a).

The opening and closing of windows was modelled using an on/off temperature control macro with a deadband of 2 K (Figure 4). This means that windows would open when room temperatures rose 1 K above the set-point temperature value, and close when dropped 1 K under the set-point value. When the outdoor temperature exceeded indoor temperature values, the windows would

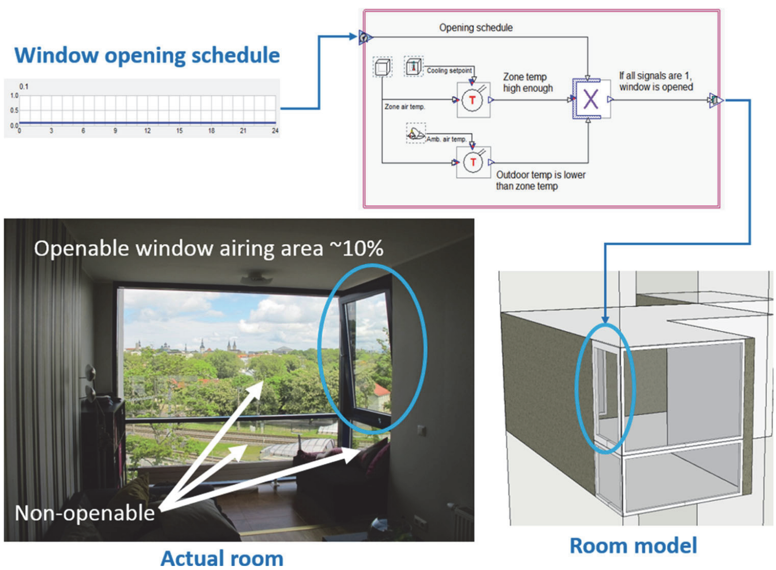

Figure 4. Window-opening control macro used in the simulations in IDA-ICE: the window is opened, when the zone temperature exceeds cooling set-point $t_{cool} + \Delta t/2$, and the outdoor temperature is lower than the room temperature; window is closed, when the zone temperature drops below $t_{cool} - \Delta t/2$. Δt is defined as deadband value.

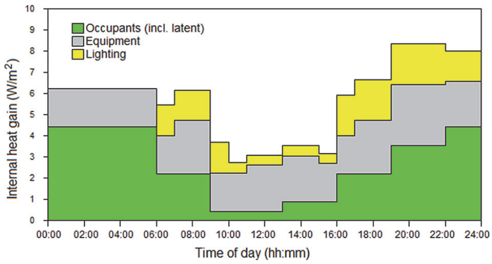

Figure 5. Internal heat gain profiles for lighting, equipment and occupancy in apartment buildings according to Estonian regulation No. 63 (GOV 2012a).

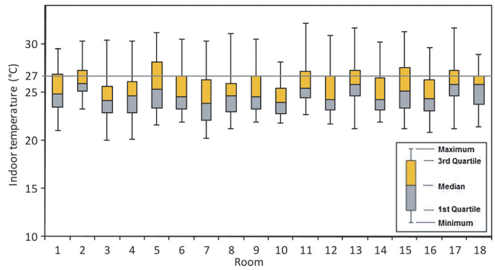

Figure 6. Measured hourly mean indoor temperatures during the period of 1 June – 31 August 2014 in studied bedrooms and living rooms.

also close (Figure 4). As the set point for opening and closing windows is not defined in the regulations, the lowest possible value for deadband 2 K was used, that is, $+22°C \pm 1$ K, which would not conflict with the heating set point +21°C. With this setting, the windows would be opened at +23°C, and closed at room temperatures below +21°C, ensuring accordance with the methodology (GOV 2012b). The openable area of the windows was calculated as a percentage of the openable window total area, depending on the height and width of the window, imitating the airing position.

Internal heat gains for dwellings were used according to regulation No. 63 (GOV 2012a): 28.3 m^2 floor area per occupant with heat emission of 125 W, including 85 W sensible heat, maximum load for equipment 3 and lighting 8 W m^{-2}. Daily occupancy and load profiles were applied to the models as shown in Figure 5.

Ventilation in dwellings was modelled with constant supply and exhaust airflow rate of 0.5 l s^{-1} m^{-2} (GOV 2012b). In apartments with central mechanical exhaust ventilation, the supply air temperature was taken to be equal to the outdoor temperature. For apartments with local air-handling units (AHUs), the rise in the supply air temperature of 1 K was accounted, due to the supply fan heat emission. Considering the bypass option of domestic AHUs, the heat exchanger effect was not modelled.

3. Results and discussion

3.1. Measurements results

The field measurement results of hourly mean indoor temperatures in bedrooms and living rooms are presented in Figure 6. The constant line of +27°C temperature in figures shows the maximum allowed indoor temperature limit by Estonian regulation (GOV 2012b) (and by the EN 15251 standard (CEN 2007)). It is shown that in some cases, temperatures over +30°C are experienced, giving clear evidence of overheating. Most of the periods with temperatures over +27°C occur at the end of July and at the beginning of August, during the warmer summer periods with outside air temperatures reaching +30°C as well (Figure 2, right). The calculated temperature excess $DH_{+27°C}$ for the measurement period was exceeding the 150 Kh limit value in 17 out of 18 (94%) of the rooms. However, this excess rate cannot be considered as noncompliance with regulation, because of the differences in standardized simulation-based compliance procedure and real situation in the dwellings, as well as the differences in weather data, especially the warmer outdoor temperature compared to TRY. The highest excess value was calculated for room #10 with 2110 Kh, which was two times higher than the excess for the next room in line, #16 with 1053 Kh.

To analyse the design-induced reasons behind overheating risk, correlations between the indoor temperature excess and the main parameters that characterize architectural design and passive measures, which have an influence on the indoor temperature, have been given.

One such measure for combating high temperatures is ventilative cooling through operable windows. To compare the passive cooling potential of different rooms, we used a parameter defined as openable area divided by total area of the windows (OA). Comparison between the indoor temperature excess $DH_{+27°C}$ and OA show quite good correlation with a statistical significance $P < .01$, even without considering differences in shading or orientation (Figure 7, left). Considerably lower DH is calculated for rooms with OA higher than 0.05. The same peak levels, around 400 Kh, have rooms with the maximum OA of 0.1 and in-between, suggesting that the OA should be in any case at least 0.05 to provide sufficient airing area.

When considering other factors, such as window-to-wall ratio (WWR) and solar heat gain coefficient or g-value, no clear correlation was found. However, when limiting the selection to only south- and west-oriented rooms and using the combination of WWR and g-value, an acceptable correlation was achieved (Figure 7, right). The chart indicates that WWR·g-value below 0.2 is recommended ($DH_{+27°C} < 400$ Kh) and less than 0.15 should be considered, but also the relatively low number of measured cases and significance of the statistical data ($P = .07$) need to be accounted.

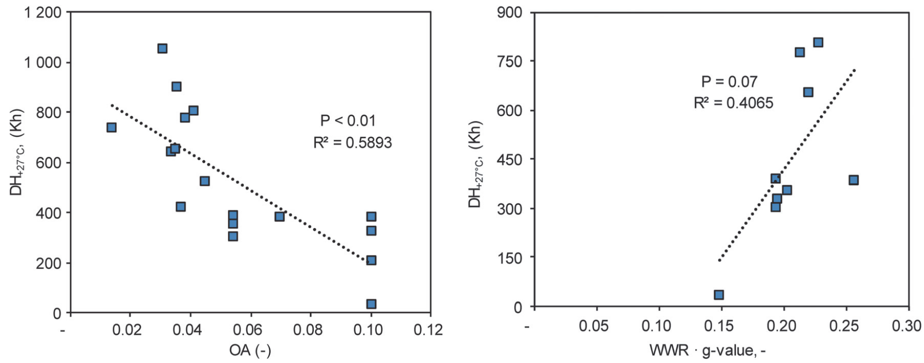

Figure 7. Indoor temperature excess $DH_{+27°C}$ dependence on openable window area to total window area (OA) (left) in all the measured rooms and on window-to-wall ratio (WWR) multiplied by window g-value (right) in south- and west-oriented rooms.

3.2. Simulations results

From the total of 158 simulated bedrooms and living rooms, 52 reached indoor temperature excess $DH_{+27°C}$ values higher than 150 Kh, the same number of rooms had no temperature excess and the rest ($N = 54$) had $DH_{+27°C}$ values in between. The temperature duration curves for all the simulated rooms are shown in Figure 8. In some cases, temperatures below 19°C were experienced, as during the summertime, room heating is not used and it was also not accounted in the simulations. In Figure 9, 'worst-case' rooms for each building have been presented. Altogether, in 17 out of 25 (68%) simulated buildings, temperature excess $DH_{+27°C}$ in at least one of the bedrooms or living rooms exceeded the limit value of 150 Kh, meaning that the building can be considered non-compliant according to the Estonian regulation (GOV 2012b). As for the standardized simulations, internal gains from occupants, lighting and equipment, as well as ventilation airflow rates per floor area, are identical across all the different buildings,

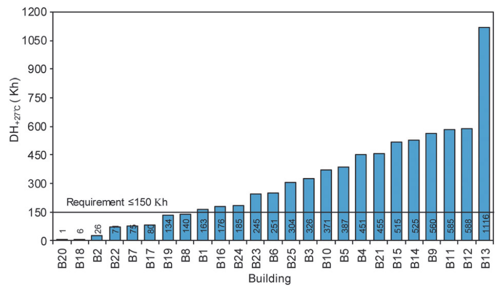

Figure 9. Simulated room temperature excess $DH_{+27°C}$ in 'worst-case' rooms in studied apartment buildings during the period from 1 July to 31 August. Requirement for compliance is $\leq$ 150 Kh (GOV 2012b).

and the large differences in temperature excess are caused mainly due to solar heat gains. In higher buildings, shades from other structures and foliage do not reach the upper floor dwellings, resulting in constant exposure to direct solar radiation. Large glazing areas with clear glazing, in combination with small openable windows, can result in extremely high indoor temperatures, as was the case with building B13.

When comparing measurement results to simulation results, it has to be accounted that there are many important variables, which are influencing the results and are disregarded in the standardized simulations made according to the methodology, aside from the weather data differences. As concluded in several studies (Rijal et al. 2008; Schweiker et al. 2012; Widen, Molin, and Ellegard 2012; Feng, Yan, and Hong 2015; Yao et al. 2015), the occupants' behaviour cannot be considered deterministic. For example, occupancy density and presence profile, which affects internal heat gains as well as opening and closing windows, which can have a substantial effect on the indoor temperature. Also, as we did not track occupants' presence

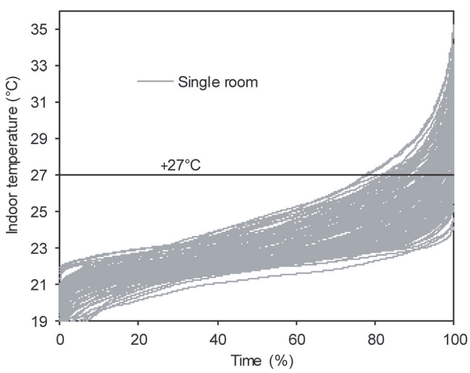

Figure 8. Simulated cumulative indoor air temperature in living rooms and bedrooms.

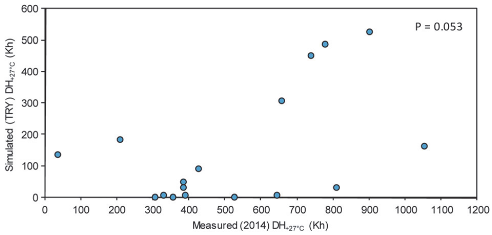

Figure 10. Correlation of temperature excess $DH_{+27°C}$ in dwellings between measurements, conducted in summer 2014, and simulations using climate data from Estonian TRY.

in dwellings, it is possible, that during the warmer periods, the dwelling was unoccupied and windows were not operated, resulting in higher temperature excess values for the measured cases (Figure 10). It can be seen that in some cases, the temperature excess values between the measured and simulated cases can be similar (e.g. room #22) as well as slightly (room #14) or significantly (room #8) different, with mostly higher values for measured cases. To some extent, it is an indication of the room use and window-opening operations, which can be close to the standard use profile. However, most cases gave higher excess values with measurements, which, to some extent, could be explained with higher outdoor temperatures during the measurement period in 2014 compared to TRY (Figure 1), resulting in an average of 300–400 Kh higher temperature excess.

In order to better compare the simulated rooms and to illustrate the effects of different parameters, in some cases, we included also simulated rooms in which temperatures did not reach the $+27°C$ mark, by using a lower base temperature of $+25°C$ ($DH_{+25°C}$) for calculating the temperature excess.

Indoor temperature simulation results, when looking at the rooms with $DH_{+27°C} < 0$ (Figure 11(a)), show practically no correlation between the indoor temperature excess and OA; in case of rooms with $0 < DH_{+27°C} < 150$ Kh (Figure 11(b)), we can see weak correlation, and for rooms with $DH_{+27°C} > 150$ Kh (Figure 11(c)), there is a relatively strong correlation with good statistical significance, showing that in rooms with high overheating risk, larger openable window area can decrease the indoor temperature excess.

In Figure 12, dependence between the temperature excess $DH_{+25°C}$ and WWR·g-value is shown. In rooms with external shading elements, there is no significant correlation, whereas in rooms without external shading, the higher WWR·g-values result also in higher temperature excess values. Roughly, WWR·g-value lower than 0.2 shows similar temperature excess values with shaded rooms.

Figure 13 illustrates the influence of WWR in south- and west-oriented rooms with external shading (left) and without external shading (right). In addition to what the previous comparison indicated, the use of shading elements has significant impact on higher room temperatures, resulting in lower temperature excess values and also, in most cases, lower the overheating risk, in case of larger windows. Another important variable, as also found in case of measurements, is OA (Figure 13, right). Higher OA values, in combination with low WWR and no shading, result also in lower temperature excess values. In this case, OA

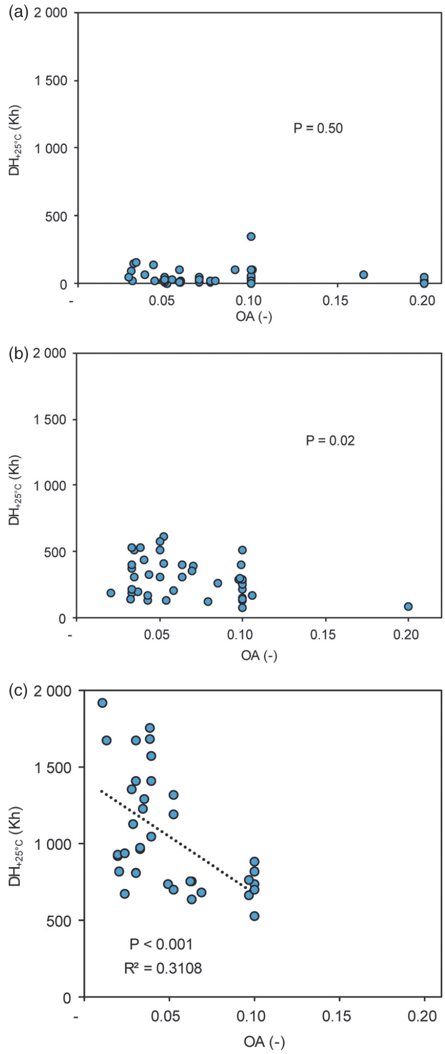

Figure 11. Dependence between the simulated indoor temperature excess $DH_{+25°C}$ and openable window area to total windows area ratio (OA) in rooms with the calculated temperature excess over $+27°C$ of 0 Kh (a), < 150 Kh (b) and ≥ 150 Kh (c).

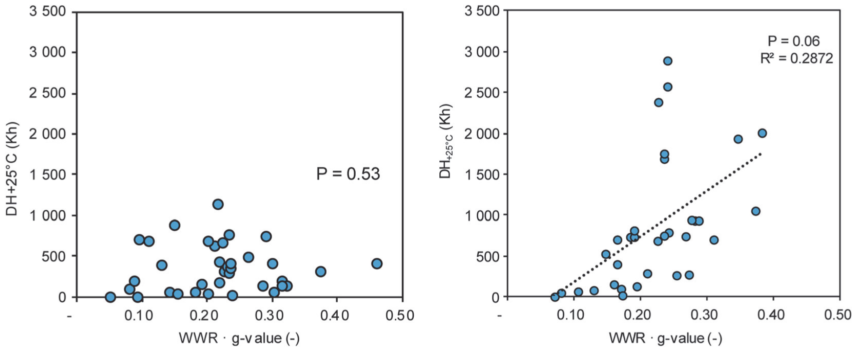

Figure 12. Simulated indoor temperature excess $DH_{+25°C}$ dependence on window-to-floor area ratio (WWR) multiplied by window *g*-value in rooms with external shading elements (left) and without shading (right).

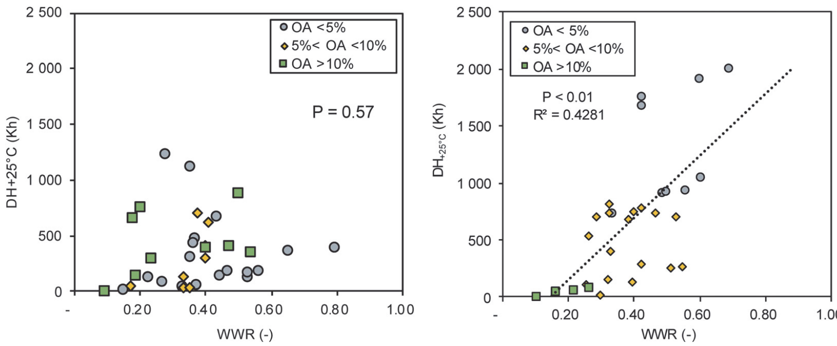

Figure 13. Simulated indoor temperature excess $DH_{+25°C}$ dependence on window-to-wall ratio (WWR) in south- and west-oriented rooms with external shading elements ($N = 37$) (left) and without shading ($N = 35$) (right). Total openable area ratio of windows (OA) is shown in three percentage levels.

over 5% and WWR under 0.4 give similar results with shaded variants. Rooms with combination of WWR less than 0.3 and OA greater than 10% show very low excess values, even with the base temperature of +25°C.

When no intentional shading options are introduced – as was the case in almost every studied building – balconies can act as the most effective shades. In south-facing rooms, with high sun elevation during summertime, balcony overhangs can contribute the most to direct sun radiation blocking. In west-facing rooms, on the other hand, the sun elevation is low, so left-sided fins have the biggest effect in case of balconies (Figure 14). In order to have a significant shading effect, it is considered that for overhangs, the ratio of overhang length ‘A’ divided by the height from overhang to the lowest part of the window ‘H’, was found to be at least ($A/H =$) 0.7 and for side-fins, the ratio of side-fin length ‘B’ divided by width from side-fin to the farthest side of the window ‘C’ as well was at least ($B/C =$) 0.7 (Figure 14). In this case, the purpose is not to fully block direct sunlight, but to reduce it for sufficient amount. Of course, better results can be achieved by using specific shading, for example, external or between-the-panes horizontal venetian blinds for south façade windows and vertical blinds for west façade windows, to ensure maximum shading and minimal negative effect on daylight and outside view. In Figure 15, box plot of simulated temperature excess $DH_{+27°C}$ in rooms with different orientation and shading is given. Most problematic are west-oriented rooms with no shading, with every case over the allowed limit, but also rooms with too short side-fins or wide windows ($B/C < 0.7$). In south-oriented room cases, the results are similar for rooms without shading and rooms with insufficient shading overhangs with $A/H < 0.7$. In both south- and west-oriented rooms, using sufficient shading, with $A/H > 0.7$ and $B/C > 0.7$, respectively, results in acceptable indoor temperature excess. In every case, in north- and east-oriented rooms, the temperature excess was below the requirement limit. This can be

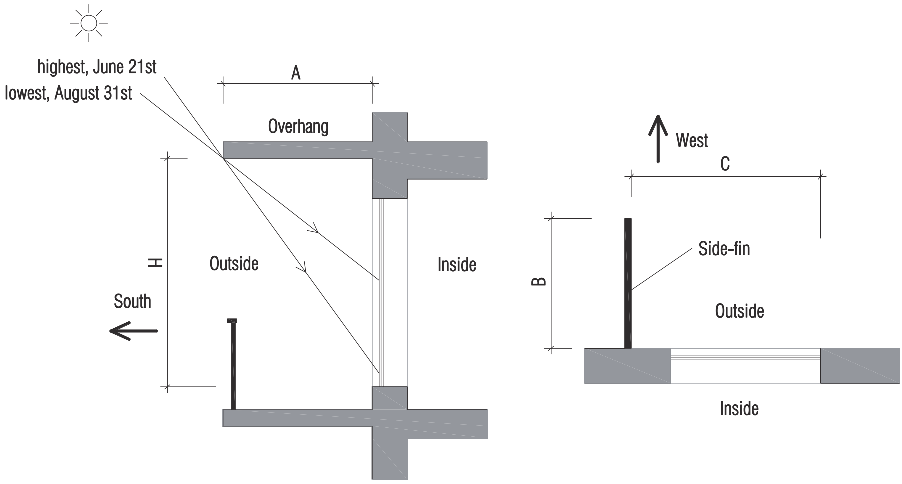

Figure 14. Examples of effective shading. For south-facing windows: (balcony) overhang with $A/H > 0.7$ (left) and for west-facing windows: (balcony) side-fin with $B/C > 0.7$ (right).

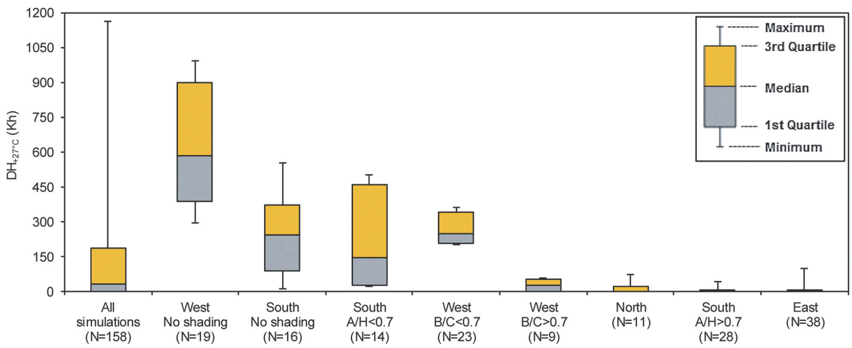

Figure 15. Simulated indoor temperature excess $DH_{+27°C}$ in dwellings: influence of orientation and shading. N, number of simulated rooms.

explained with the low levels of direct solar radiation in north orientation and lower outdoor temperatures in the morning in east-oriented rooms.

4. Conclusion

In this study, we have measured the indoor temperature in 22 dwellings in 16 new apartment buildings, during a three-month summertime period from 1 July to 31 August 2014. Results show that in several cases, hourly mean room temperatures did rise as high as $+32°C$ and majority of the dwellings were experiencing temperatures over $+27°C$ for a remarkable portion of the measuring period, presenting clear evidence of overheating.

The summer thermal comfort compliance assessment of the studied buildings was conducted in accordance with the Estonian regulation No. 63 ‘Methodology for calculating the energy performance of buildings’ (GOV 2012a) – the indoor temperatures in the selected dwellings were simulated using dynamic simulation software IDA-ICE and climatic data from TRY with standardized input parameters for internal heat loads and usage profiles. In total, 158 rooms from 25 buildings were simulated. The simulation results show that 17 out of 25 (68%) of the studied apartment buildings do not comply with the summer thermal comfort requirements of Estonian regulation No. 68 ‘Minimum requirements for energy performance’ (GOV 2012b). The main reasons for non-conformity are the use of large windows without shading and insufficient area of operable windows.

Comparison between the measured and simulated indoor temperature excess values for the same rooms indicates that differences between real year and reference year climatic data, real and standardized occupancy profiles, internal gains, window openings, etc. are too significant for definitive measurement-based overheating assessment. Therefore, in the case of high temperatures perceived or measured, it is recommended to conduct a temperature simulation to assess the possible non-compliance with the regulation.

Analysis of the measured and simulated results shows that shading balconies can have the largest effect on overheating risk reduction. As a rule of thumb, in south-oriented rooms, overhangs with length to window height ratio over 0.7 and side-fins, in case of west-oriented rooms, with the side-fin length to window width ratio also at least 0.7, were found sufficiently effective. However, the relatively small sample size should be taken into account. Secondly, the WWR·g-value under 0.2 showed in both measured and simulated cases lower temperature excess values. Lastly, it was found that the total openable area of windows should be at least 5%.

For a guideline, for selecting the 'critical rooms', that is, bedrooms or living rooms most likely to counter overheating, the defining parameters are found to be mainly a combination of different attributes, such as: south- and/or west-oriented windows, lack of external shading elements or insufficient dimensions of the shading, with WWR values over 0.4 or WWR·g-values over 0.2 and total windows' airing area lower than 5%.

In north- and east-oriented rooms, significant correlations between shading, airing area or WWR was not found, and also, no exceedance of temperature excess limit was registered. This can be explained with the low levels of direct solar radiation in north orientation and lower outdoor temperatures in the morning in east-oriented rooms.

It can be concluded that this relatively new building code requirement was not fully established in practice. Results show that the requirement in apartment buildings is achievable without cooling, if passive measures are properly applied. As an important outcome of the study, to mitigate the risk of overheating in new, planned residential buildings, it is recommended for authorities to pay more attention for EPC (random) checks and to check also within this process the availability and plausibility of overheating temperature simulation reports. It is also advised that the overheating parameters be covered in more detail in EPC checks.

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Experimental validation of simulation and measurement-based overheating assessment approaches for residential buildings

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ABSTRACT
As a part of the building design process, Estonian building code requires standardized dynamic hourly simulations to verify the building's compliance to the summer thermal comfort requirements. In this study, we analysed this overheating assessment method for free-running residential buildings, by comparing the simulation results with measured data. Simulation models with different thermal zoning levels were studied: single-zone models, multi-zone apartment models and multi-zone whole building models. We analysed and quantified the effects of modelling detail and thermal zoning on indoor temperature and overheating estimation on the basis of five apartment buildings. Based on the results, a method, using indoor temperature measurements and outdoor climate data, to assess overheating risk has been proposed, as a relatively simple and inexpensive method for pre-defining the need for dynamic simulations.

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Domestic buildings; free running; temperature measurements; assessment methods; IDA-ICE; thermal zoning

1. Introduction

During the past decades, computer-based building modelling and simulation has become a common practice among engineers and architects (Attia et al. 2012), mainly with a goal to estimate the energy consumption of planned buildings. With the rapid evolution of building simulation tools and increase in computing power, more detailed and advanced models can be created and analysed, to imitate real buildings in operation. Aside from energy consumption estimation, accurate and detailed simulations of indoor climate parameters have been made possible (Wang and Zhai 2016).

With the trends in architecture and envelope design, namely the extensive usage of unshaded glazed façades and highly insulated airtight walls, an increasing number of low-energy buildings are built with a tendency to overheat (Mavrogianni et al. 2012; Chvatal and Corvacho 2009). These cases occur not only in warm climate countries but also in temperate and cold climate countries (Rohdin, Molin, and Moshfegh 2014).

Assessing the risk of overheating in buildings is rather a difficult and time-consuming task. The use of detailed dynamic simulations is becoming the mainstream method practised among architects and specialists, with also raising trends in analysing free-running domestic buildings. There are, however, numerous important variables causing differences between real situation and assessment results, such as occupant behaviour (Haldi and Robinson 2011), occupancy density and patterns in terms of internal gains, opening and closing windows (Schweiker et al. 2012), shading and air movement dynamics, which are difficult to predict (da Silva, Leal, and Andersen 2015). To reduce the complexity of such analysis, some forms of standardized methods are practised in different parts of the world (Jenkins et al. 2013). For example, in the UK, a simplified static calculation assessment method can be used for residential developments (Tillson, Oreszczyn, and Palmer 2013; DECC 2014; Jenkins et al. 2013), in Finland on the other hand, multi-zone dynamic simulations are required by the Building Code (2012). Using the more complicated simulations to predict overheating with acceptable accuracy requires sufficiently detailed modelling with adequately defined thermal zoning, especially in case of low-energy and free-running buildings (O'Brien, Athienitis, and Kesik 2011). Simplifications in such thermal modelling and calculations are, of course, welcomed among building professionals (Kanters, Dubois, and Wall 2013), but can only to be stretched to a reasonable extent, in order to estimate building performance with an acceptable margin of error. Drawbacks of using such simplified approaches, in practice, have been also recently reported (Bateson 2016; Jenkins et al. 2013).

With the launch of European Union Directive 2010/31/EU (EU 2010), requirements for overheating prevention were established also for all new buildings in Estonia. According to the enforced Regulation No. 68 (GOV 2012b), the compliance verification calculation for summer thermal comfort in residential buildings needs to be conducted for at least one living room and one bedroom, with the highest risk of overheating. As opposed to the Finnish multi-zone methodology, for example, the Estonian approach implies single room calculations, in which the heat and air transfer dynamics of the apartment or the building as a whole are not accounted.

In the recent years, several studies have been carried out in Estonia on indoor climate in apartment buildings, mostly involving buildings built before 1990s, but also on newer buildings constructed between 1990 and 2010 (Kalamees et al. 2012). It was found that 63% of the studied dwellings were overheating in summer. Maivel, Kurnitski, and Kalamees (2014) investigated

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indoor temperature-related problems in old and new apartment buildings in Estonia and found that overheating is most common in new buildings. It was also concluded that for a detailed analysis, dynamic simulations are needed.

Simson, Kurnitski, and Maivel (2016) studied the current situation regarding compliance to summer thermal comfort, and found that 68% of the new buildings built in Estonia, after the enforcement of the new regulation, did not comply with the requirements.

The aim of the study is to analyse the impact of thermal zoning on the simulation-based overheating assessment calculation and to give a temperature measurement-based 'rule of thumb' for a low-cost method for pre-assessing overheating compliance of dwellings. We have compared measured hourly average indoor temperature with results from three levels of thermal zoning – the currently used single-zone method and two multi-zone approaches: whole apartment and whole building model approach. For detailed analysis, we have selected apartments from five apartment buildings in which temperature measurements have been conducted during the summer period from 1 July to 31 August 2014. For simulations, we used the energy and indoor climate simulation software IDA-ICE (EQUA 2016). In order to compare the calculation methods for summer thermal comfort assessment, we have fitted the simulation results using the temperature measurements.

2. Methods

First, whole building models were created and simulated with well-validated software IDA-ICE (EQUA 2016), using weather data from the year of the measurements. The simulated temperature results were compared with measured indoor temperature results. Then, the models were adjusted to get acceptable margin of error and correlation with measurements. These 'fitted' models were then simulated using weather data from Test Reference Year (TRY; Kalamees and Kurnitski 2006), to get a base value for temperature excess and evaluate the buildings' compliance with overheating requirements. To analyse the impact of thermal zoning, two alternative simulation models were created by removing neighbouring zones from the original whole building model: for the first model, only the rooms in the apartment were kept and for the second model, only the analysed rooms were kept. Simulation results from the latter models were also compared with the results from the fitted whole building model.

Based on the respective simulation results using real weather data, base temperature values for temperature excess calculations were calculated for each building to get respective excess values with measurement results.

2.1. Compliance assessment

The mandatory summer thermal comfort compliance verification in Estonia, for planned buildings, is carried out according to the requirements described in Estonian Regulations No. 63, 'Minimum Requirements of Energy Performance' (GOV 2012b) and No. 68, 'Methodology for Calculating the Energy Performance of Buildings' (GOV 2012a) using dynamic computer simulations. The methodology states that overheating risk assessment has to be done for living rooms and bedrooms, with the highest potential to counter high temperatures. To quantify the overheating risk in these rooms, indoor temperature excess (DH) in degree-hours (Kh) is used, which is calculated as follows:

$$DH_{t_b} = \sum_{i=1}^{j} (t_i - t_b)^+, \qquad (1)$$

where DH_{t_b} is the temperature excess in degree-hours over the base temperature t_b, t_i is the hourly mean room temperature and j is the total number of hours in the given period. The '+' sign means that only positive values are summed. In the Estonian regulation, the maximum limit for residential buildings indoor temperature excess is 150 Kh over a base temperature $t_b = +27$°C. For the calculation period of $j = 2208$ h, that is, from 1 July to 31 August, the equation can be given as follows:

$$DH_{+27^\circ C} = \sum_{i=1}^{2208} (t_i - 27)^+. \qquad (2)$$

2.2. Weather data

According to the methodology, room temperature calculations are performed regardless of the location of the building using the Estonian TRY (Kalamees and Kurnitski 2006), also used for building energy consumption calculations. The TRY is constructed using different months from three decades (1970–2000) of climatic data that best describe Estonian climate. It contains hourly mean data of outdoor temperature, relative humidity, wind speeds and solar radiation.

The indoor temperature measurements in dwellings were performed in the summer of 2014. Compared to outdoor temperatures from TRY and a typical summer of 2013 (Figure 1), the summer of 2014 was relatively warm, with two distinctive heat waves with hourly mean outdoor temperatures reaching higher than +30°C. The outdoor DH over the base temperature +27°C in 2013 was 24.3 Kh, in 2014 157.3 Kh. In the case of TRY, the DH is 0.5 Kh (Figure 1). For the measurement year 2014, a custom climate file was created using the measured data from a nearby weather station.

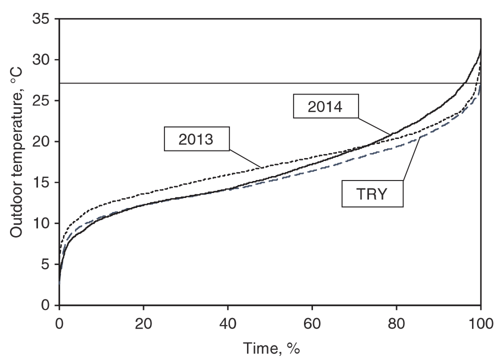


Figure 1. Hourly mean outdoor temperature duration curves for summer period from 1 July to 31 August. Data from Estonian TRY and weather station measurements [Estonian Weather Service (EMHI 2015)] in years 2013 and 2014.

2.3. Description of the studied buildings

Five apartments from five different buildings were studied, modelled and simulated. The relevant information for building structures, dimensions, site and other parameters was acquired from buildings' design documentation. Overview of the specifications of external boundaries, windows and other parameters of the buildings is given in Table 1. The studied buildings were constructed between 2011 and 2014. From each building, one apartment was selected for the analysis. Example plans and analysed rooms of the apartments are shown in Figure 2. All the buildings had apartment-based mechanical supply and exhaust ventilation units installed. Outdoor air was supplied to living rooms and bedrooms and removed from bathrooms and kitchens. The air handling units were equipped with summer bypass function for the heat exchanger. During the summer period, no heating systems were utilized in the buildings. Also, no mechanical cooling systems were installed (Figure 3).

2.4. Measurements

Indoor temperature measurements were carried out during the summer period of 1 July to 31 August 2014 in either living rooms or bedrooms in the selected apartments. For measurements previously calibrated, data logging Hobo U12 (ONSET 2015) devices were used with temperature measuring range of -20 to $+70$°C with accuracy ± 0.35 K and relative humidity 5–95% with accuracy $\pm$ 2.5% of full-scale output. The data loggers were placed in the occupied zone of the rooms, away from direct sunlight, ventilation air flows, heat-generating equipment, etc. For each measurement taken, correction factors according to calibration results were applied. Ventilation air flows from supply and exhaust valves and grilles were measured with SwemaFlow 234 air flow hood with a range of 2–65 l/s and uncertainty ± 2.5% of read value.

2.5. Simulations

The buildings were modelled with indoor climate and the energy simulation software IDA Indoor Climate and Energy, version 4.7 (IDA-ICE) (EQUA 2016). This tool allows detailed and dynamic whole-year multi-zone building simulations of indoor climate, energy consumption and building systems performance. IDA-ICE has been validated according to European Standard EN-ISO 13791 defined test cases (Kropf and Zweifel 2002), to Envelope BESTEST in the scope of IEA Task 12 (Achermann 2000) and used in several similar studies (Hamdy, Hasan, and Siren 2011; Hilliaho, Landensivu, and Vinha 2015; Jokisalo and Kurnitski 2007; Molin, Rohdin, and Moshfegh 2011).

Input data for the studied buildings, including building site surroundings, architecture, floor plans, and specifications of walls, roofs and windows were acquired from design documentation of the buildings and Estonian Registry of Buildings database (ERBD 2014).

Each material layer included properties for specific heat and density for accurate calculation of building thermal mass. Solar heat gain coefficients of windows, if not available in design documentation, were calculated using detailed window model with glazing properties calculation tool in IDA-ICE. Overall values used in buildings' simulations are shown in Table 1.

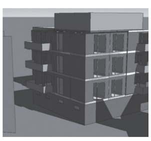
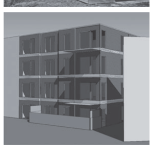
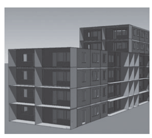
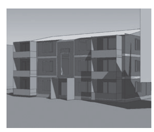
Trees, casting shades on the building, were modelled as crossing vertical rectangular planes (Table 1). The shading effect of trees and foliage was estimated as transparency factor between 0.2 and 0.3 (with 1.0 being fully transparent) (Heisler 1986).

Infiltration for the buildings was calculated using Equation (3) (GOV 2012a):

$$q_i = q_{50} \times A/(3.6 \times z), \tag{3}$$

where q_{50} is the building air permeability at 50 Pa pressure difference, m³/(h·m²); A is the total area of building envelope, m²;

Table 1. Specifications overview of the studied buildings.

Building no.	B1	B2	B3	B4	B5
Photo of the studied building					
3D view of the building model in IDA-ICE					
Construction year	2014	2012	2011	2012	2013
Envelope construction	Concrete	Concrete	Pre-cast concrete	Pre-cast concrete	Concrete block
Building height(m)	14.0	11.7	21.0	12.0	10.6
Floors above ground	4	4	6	3	3
Apartments	12	21	40	14	9
Net heated area(m²)	1 137	1 580	3 114	891	742
Volume(m³)	5 465	6 043	11 422	4 872	2 884
Ext. wall U-value(W/(m²·K))	0.20	0.16	0.17	0.21	0.19
Roof U-value(W/(m²·K))	0.12	0.14	0.09	0.12	0.13
Windows U-value(W/(m²·K))	1.10	1.00	0.89	1.10	1.20
Windows g-value	0.65	0.45	0.60	0.63	0.67

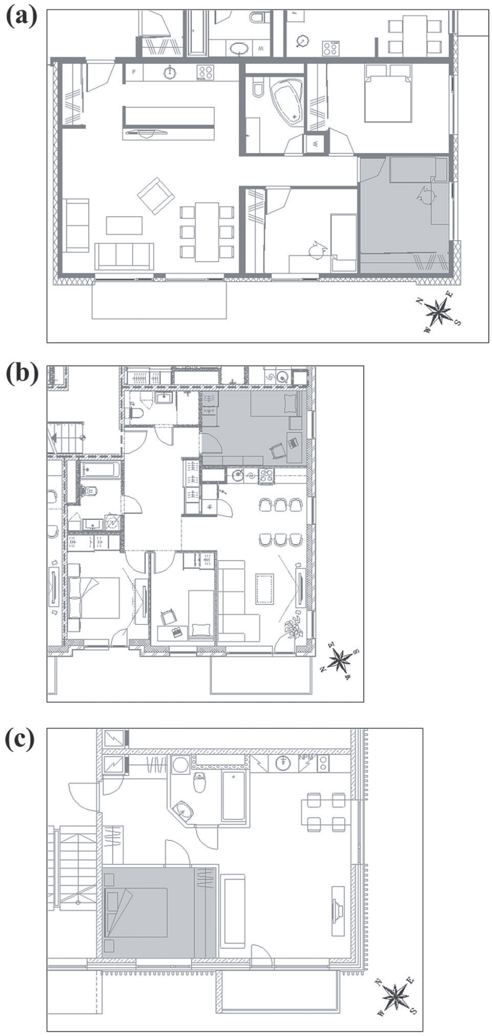


Figure 2. Example of apartment plans and analysed rooms (highlighted) of the studied buildings: bedroom, B1 (a); bedroom, B2 (b) and bedroom, B4 (c).

and z is the building height factor: 35 for one, 24 for two, 20 for three and four and 15 for five and higher storey buildings. In all cases, building air permeability value 3 $m^3/(h \cdot m^2)$ was used, as intended for calculations in new buildings, according to GOV (2012a).

The opening and closing of windows was modelled using on/off temperature control macro with a dead band of 2 K (Figure 4). This means that windows would open, when room temperature raised 1 K above the set point temperature value, and close, when dropped 1 K under the set point value. In this case, the set point was chosen +22°C, ensuring window openings at +23°C, and closings at room temperatures under +21°C. When outdoor temperature would exceed indoor temperature values, the windows would also close. The openable area was calculated as a percentage of the openable window total area, depending on the height and width of the window, imitating the airing position.

The regulation (GOV 2012a) gives values for the whole dwelling's internal gains as follows: 28.3 m^2 floor area per occupant with heat emission of 125 W, including 85 W sensible heat; 3 W/m^2 accounting equipment and 8 W/m^2 for lighting. The occupancy and load profiles are shown in Figure 5. Ventilation in zones was modelled as well mixed with constant supply and exhaust air flow rate of 0.5 $l/(s \cdot m^2)$ (GOV 2012b). In apartments with central mechanical exhaust ventilation, the supply air temperature was taken equal to outdoor temperature. In apartments with local air handling units (AHUs), supply air

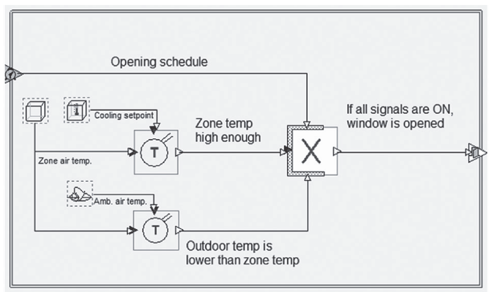


Figure 4. Window opening control macro in IDA-ICE used in simulations. Window opens if zone temperature exceeds cooling setpoint t_{cool} $+\Delta t/2$, and outdoor temperature is lower than room temperature, window closes when the zone temperature drops below $t_{cool} - \Delta t/2$. Δt is defined as dead band value.

Figure 3. Photos from the studied rooms: (from left) bedroom, building B1; bedroom, building B2; living room, building B3; living room, building B4 and bedroom, building B5.

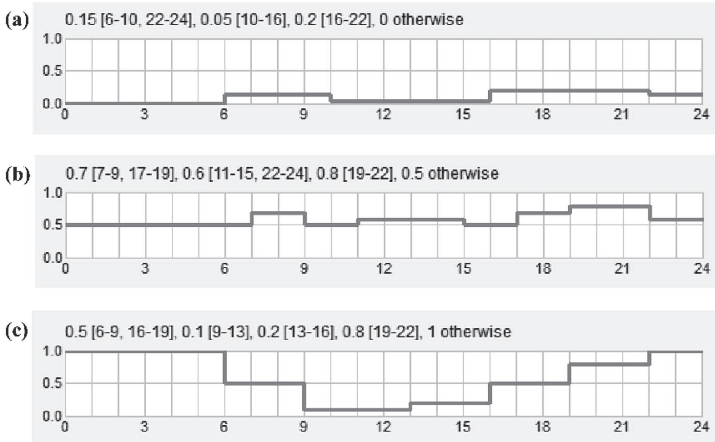


Figure 5. Hourly profiles for lighting (a), equipment (b) and occupancy (c) used for internal heat gains calculation according to Estonian Regulation No. 63 (GOV 2012a).

temperature was considered 1 K higher than outdoor temperature due to the supply fan heat emission. Considering the bypass option of domestic AHUs, heat exchanger effect was not accounted.

2.5.1. Thermal zoning

We used three different thermal zoning approaches for building modelling (Figure 6):

- multi-zone approach, with all the rooms in the building modelled;
- multi-zone approach, with only rooms in the apartment modelled;
- single -zone approach, with only the analysed room modelled.

In case of the apartment-based method, thermal connections, as well as air leakages between other rooms and neighbouring apartments, openings and boundaries were not accounted – heat and air transfer was modelled only between the rooms in the apartment and outdoor environment, for example, external walls, internal walls and windows. The single-zone method accounted only for connections with external walls and windows, and the neighbouring sides of internal constructions were modelled as adiabatic. The multi-zone method, however, accounted connections between all the rooms in the apartment. In the single-zone method, both supply and exhaust ventilation was modelled as room-based.

An example schematic view of the whole building model in IDA-ICE simulation environment (SE) is presented in Figure 7. The IDA-ICE SE is a general-purpose modelling and simulation tool for modular systems where components are described with mathematical equations, written in the Neutral Model Format. More detailed information, for the component modules and IDA solver, can be obtained from several publications (Vuolle and Sahlin 2000; Björsell et al. 1999; Vuolle and Sahlin 1999; Kalamees 2004; EQUA 2016). The largest whole building model, with 153 thermal zones, was created for building B3, which had 40 apartments.

2.6. Evaluation of simulation results

First, the fully detailed building models were calibrated into acceptable agreement with the temperature measurements

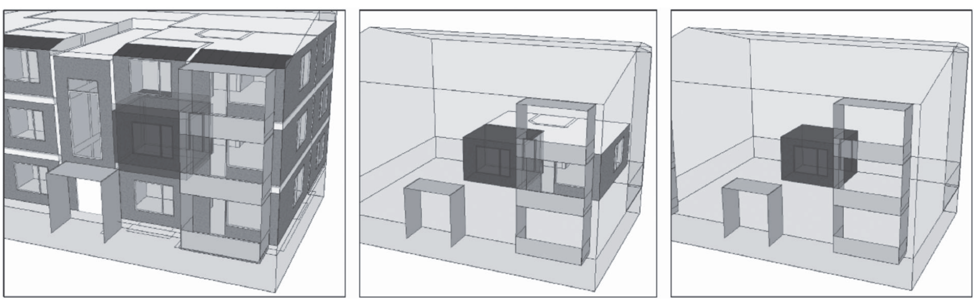


Figure 6. Simulation model detail for different calculation methods: whole building model (left), apartment without neighbouring zones (middle) and single room model (right).

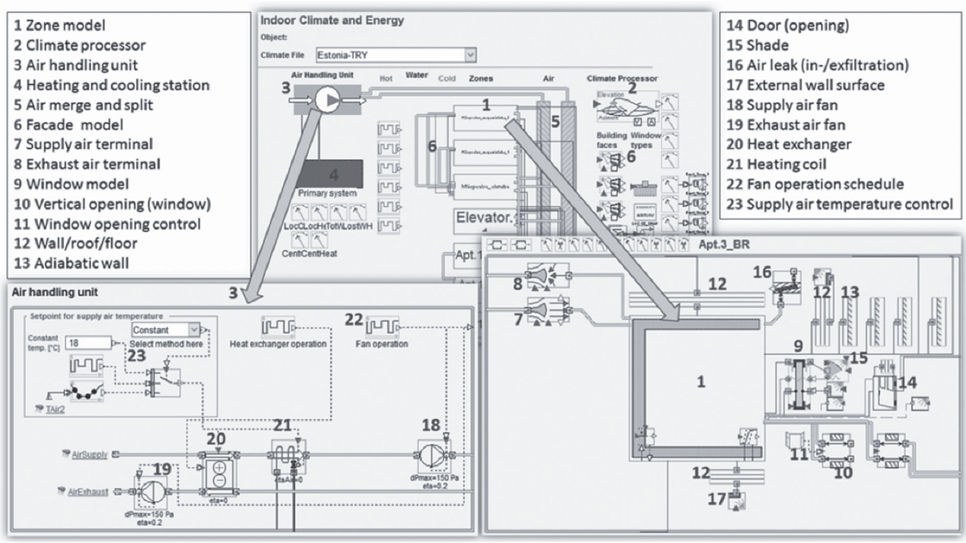


Figure 7. Schematic view of the IDA-ICE environment: example of a whole building model fragment.

from one-month measuring period by changing internal gains, temperature set points for window opening control and by adding internal drapes to the window models. The correlation between the measured and simulated indoor temperature was assessed by linear regression analysis, using Pearson correlation coefficient as one of the indicators.

In order to validate the calibrated models, we used the coefficient of variation of the root mean squared error, CV(RMSE) (4) and the mean bias error (MBE) (5) to quantify the overall accuracy of the simulations (Draper and Smith 1981):

$$\mathrm{CV(\,RMSE)}\ (\%) = \frac{\sqrt{\sum_{i=1}^{n}(\mathrm{Sim}_i - \mathrm{Meas}_i)^2/n}}{\overline{\mathrm{Meas}}} \times 100\%, \tag{4}$$

$$\mathrm{MBE}(\%) = \frac{\sum_{i=1}^{n}(\mathrm{Sim}_i - \mathrm{Meas}_i)/n}{\overline{\mathrm{Meas}}} \times 100\%, \tag{5}$$

where Meas_i is the measured value of the variable, Sim_i is the simulated value of the variable, $\overline{\mathrm{Meas}}$ is the mean value of the measured variable and n is the number of data points. The CV(RMSE) is essentially the root mean squared error divided by the measured mean of the data (Haberl and Thamilseran 1994). Comparisons were conducted in terms of predicted indoor temperatures. The CV(RMSE) of the hourly simulation results and measured data were calculated (Bou-Saada and Haberl 1995).

To evaluate the quality of the simulation results, additional parameters are used, such as average error percentage (6), average difference between measured and simulated results (7) and average bias (8) for the specified period:

$$\mathrm{Avg.\ Error}(\%) = \sum_{i=1}^{n}\left|\frac{\mathrm{Sim}_i - \mathrm{Meas}_i}{\mathrm{Meas}_{\mathrm{Max}} - \mathrm{Meas}_{\mathrm{Min}}}\right| \times \frac{100\%}{n}, \tag{6}$$

$$\mathrm{Avg.\ Dif}(\,K) = \frac{\sum_{i=1}^{n}|\mathrm{Sim}_i - \mathrm{Meas}_i|}{n}, \tag{7}$$

$$\mathrm{Avg.\ Bias}(K) = \frac{\sum_{i=1}^{n}(\mathrm{Sim}_i - \mathrm{Meas}_i)}{n}. \tag{8}$$

3. Results and discussion

3.1. Model calibration

An example of a model calibration result of a living room for 8-day heat wave period is shown in Figure 8. The simulation results of the calibrated building models for two extreme cases, in terms of DH, are presented in Figure 9. The goal for the validation was to achieve CV(RMSE) values under 5%. It is shown that the validation results show acceptable agreement with the measurements (Figure 10).

3.2. Simulation results for different thermal zoning cases

The simulation time for the largest whole building model, using a high-performance personal computer (housing an Intel© Core™ i7-5820 K processor), was 3 h and 14 min. In comparison, for the apartment-based model with three zones, the simulation time was 1 min and for the single zone model, 8 s.

The calculated simulation evaluation parameters from different thermal zoning methods are shown in Table 2. The average error increases, when simplifications are applied to the whole building models. It can be seen that although CV(RMSE) values in full apartment simulation method and single-zone method remain in similar proportions, the average error is over 10% in four whole apartment model cases and single-zone model cases as well. Results acquired using the single-zone method show mostly lowest agreement with the measurement results, however, being quite close to the apartment-based cases. In four

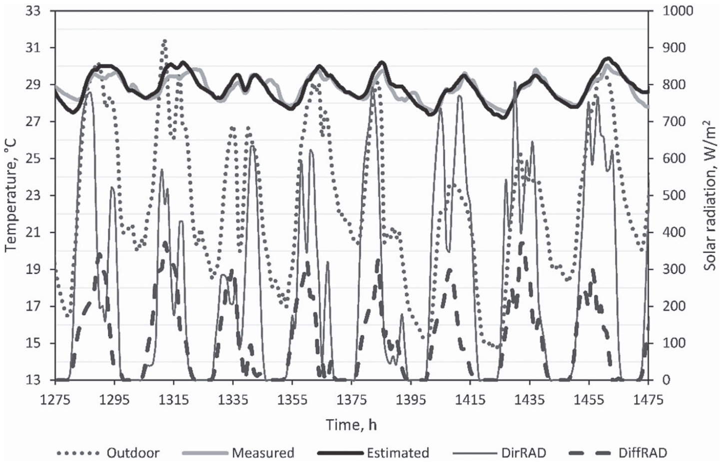


Figure 8. Model validation results of simulated living room (building B4) temperature, 8-day period during the heat wave in 2014 summer. Code: outdoor: ambient temperature; measured: measured indoor temperature; estimated: simulated indoor temperature; DirRAD: direct normal solar radiation; DiffRAD: diffuse solar radiation on horizontal surface.

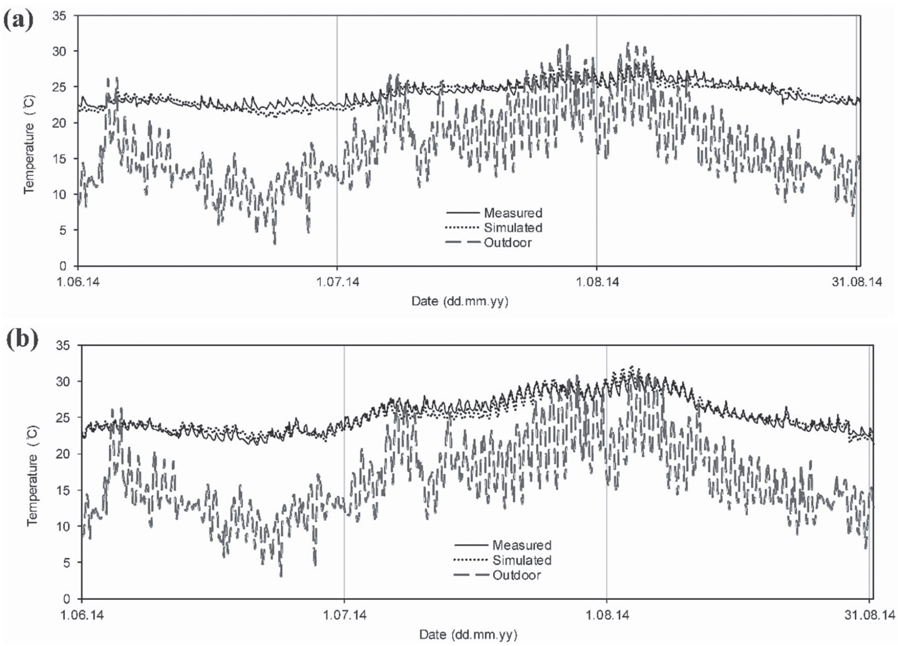


Figure 9. Examples of model validation results: measured and simulated hourly average indoor temperature in selected rooms during the summer period of 1 July to 31 August 2014. Room with the lowest measured temperature excess (DH) – bedroom in building B5 (a) and room with the highest measured DH: living room in building B5 (b).

cases, comparing apartment and single room modelling results, the single room cases give higher DH values, except for the case with building B4, in which the single room method gives lower value. The small change in error values, regarding building B5, could be accounted for the shade casting neighbouring buildings and trees, limiting the effect of direct solar radiation to the building.

Table 3 shows the difference between using standard values for occupant profiles and internal gains according to the methodology (GOV 2012a) and real thermal situation through

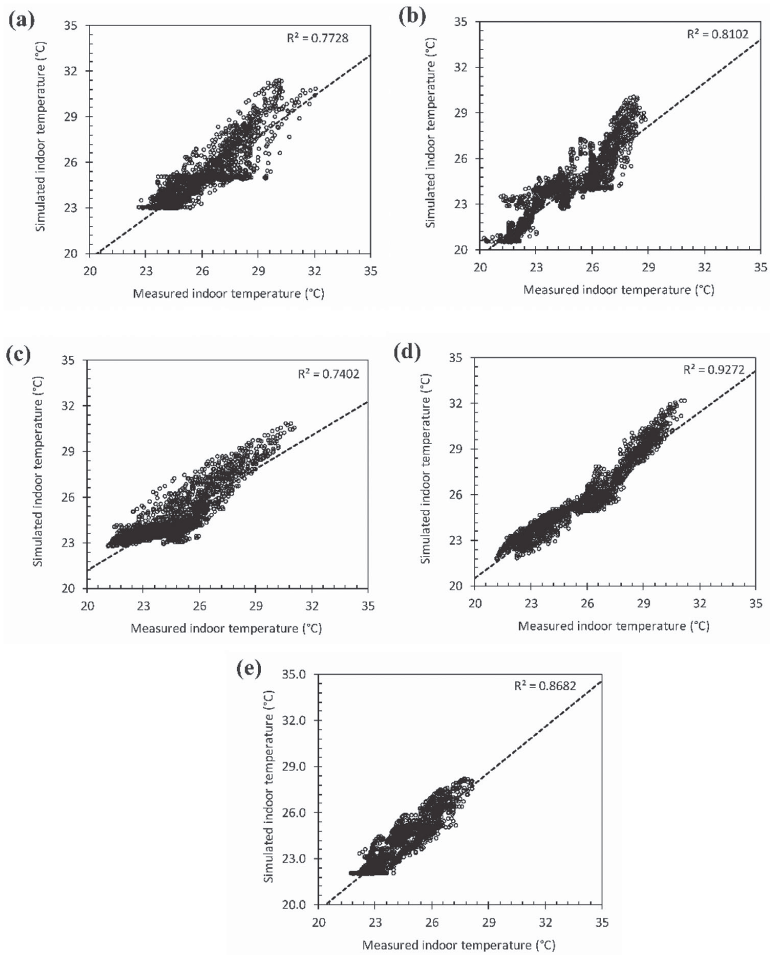


Figure 10. Model validation results: comparison of 2208 h of measured and estimated indoor temperature values: bedroom in building B1 (a), bedroom in building B2 (b), living room in building B3 (c), living room in building B4 (d) and bedroom in building B5 (e).

measurements in the studied rooms. The whole building model and apartment model give mostly lower DH results, as the single-zone method gives higher values for the cases with lower measured DH.

Three of the DH values for single-zone models (B1, B3 and B4), modelled and simulated according to the Estonian methodology (GOV 2012a), are higher compared to the multi-zone model results (Table 4). However, in two cases (B2 and B5), the single-zone model gives lower values. This occurs most likely due to the high temperatures in the neighbouring zones, which is not accounted, in case of the single-zone model, or thermal load shifting due to the movement of the sun and the effect of direct solar irradiation. As the standardized, single-zone simulation results define also the compliance according to the current methodology, it can be seen that rooms, which encountered remarkable overheating in reality, show also non-compliance with the single-zone simulations. The whole building model and apartment model, however, in building B1, do not indicate non-compliance. The latter case, also when comparing simulations made with climate data from 2014, can be explained with higher internal gains, closed doors between the rooms or lack of window airing in practice, during the measurement period.

3.3. Proposed methodology for measurement-based overheating assessment

Although overheating assessment by calculations for a building in planning stage is required with the state regulations in order to acquire a building permit, the importance of this procedure is often underestimated and calculations are usually done poorly, if at all (Simson, Kurnitski, and Maivel 2016; Tuohy and Murphy 2015). In such cases, it is extremely difficult for the tenant to prove the existence of the problem, as it is only defined as a requirement and a method for evaluating building designs and

Table 2. Evaluation results of the indoor temperature simulations for different modelling detail.

Building no.	Avg. error, (%)	Avg. dif. (K)	Avg. bias (K)	CV(RMSE) (%)	MBE (%)	$DH_{+27°C}$, (Kh)
Measured						
B1	–	–	–	–	–	777
B2	–	–	–	–	–	209
B3	–	–	–	–	–	354
B4	–	–	–	–	–	1053
B5	–	–	–	–	–	35
Calculated: whole building model (fitted)						
B1	7.6	0.8	1.6	4.7	−2.5	765
B2	9.9	0.9	1.3	4.3	−2.1	211
B3	9.6	0.8	1.0	4.1	−0.2	360
B4	5.5	0.6	0.4	1.8	0.1	1065
B5	6.0	0.6	0.5	2.1	−1.5	50
Calculated: apartment model (neighbouring zones removed)						
B1	11.7	1.1	1.7	6.7	−3.7	535
B2	13.7	1.2	2.0	7.9	−3.6	265
B3	10.3	0.9	1.2	5.0	1.9	277
B4	13.9	1.4	3.2	12.4	−4.5	813
B5	6.6	0.6	0.5	2.2	−1.5	29
Calculated: single zone model (neighbouring zones removed)						
B1	12.5	1.1	1.7	6.7	−3.3	641
B2	13.8	1.2	2.0	7.9	−3.2	448
B3	12.1	1.0	1.9	7.6	3.4	936
B4	17.5	1.5	3.6	14.2	−5.1	676
B5	7.6	0.7	0.7	3.0	0.4	230

Table 3. Evaluation of simulated temperature results for different thermal zoning methods using standard values according to the methodology (GOV 2012a) and climate data from summer 2014.

Building, room	B1, bedroom				B2, bedroom				B3, living room				B4, living room				B5, bedroom			
Thermal zoning	MEAS	BLD	APT	SZ	MEAS	BLD	APT	SZ	MEAS	BLD	APT	SZ	MEAS	BLD	APT	SZ	MEAS	BLD	APT	SZ
$DH_{+27°C}$ (Kh)	777	478	535	641	209	190	152	358	354	298	277	936	1053	527	813	676	35	29	39	230
Min temp. (°C)	22.7	23.0	23.0	22.9	20.3	20.4	20.4	20.4	21.2	21.9	21.9	22.0	20.3	20.9	19.2	19.2	21.7	22.0	22.0	21.9
Max temp. (°C)	32.1	31.3	31.7	32.5	28.9	29.9	29.6	30.7	31.1	30.5	30.4	32.7	31.2	30.4	31.7	31.6	28.2	27.9	28.2	30.4
Avg. temp. (°C)	25.8	24.9	24.9	25.0	24.8	23.1	23.0	23.2	24.7	25.2	25.2	25.5	25.3	25.3	24.3	24.1	24.1	23.7	23.7	24.2
Avg. error (%)	–	12.7	9.9	12.6	–	21.0	21.2	20.8	–	10.2	10.5	12.3	–	7.1	10.5	15.0	–	7.0	5.3	7.6
Avg. dif. (K)	–	1.1	1.1	1.1	–	1.8	1.8	1.8	–	0.9	0.9	1.1	–	0.8	1.2	1.3	–	0.6	0.6	0.7
Avg. bias (K)	–	1.8	1.7	1.7	–	4.5	4.6	4.3	–	1.2	1.3	1.9	–	0.9	1.9	2.4	–	0.5	0.5	0.7
Max. dif. (K)	–	4.5	4.5	4.5	–	4.8	4.8	4.3	–	3.5	3.5	4.5	–	3.2	3.4	3.7	–	2.3	2.2	2.7
CV(RMSE) (%)	–	6.8	6.7	6.8	–	18.3	18.5	17.5	–	4.9	5.1	7.7	–	3.7	7.6	9.6	–	2.2	2.1	2.9
MBE (%)	–	−3.8	−3.6	−3.4	–	−6.9	−7.1	−6.3	–	2.0	2.1	3.5	–	−0.1	−4.2	−4.9	–	−1.6	−1.6	0.3

Code: MEAS: measured room; BLD: whole building model; APT: apartment model; SZ: single zone model.

not as an assessment for existing buildings. If the calculations have not been conducted, the acquisition of input data, regarding envelope structures, technical drawings, etc. can be difficult. For such cases, estimating the simulation results, based on real indoor temperature measurements, could act as an efficient and low-cost method.

Different studies have indicated that there is a relatively strong correlation between outdoor and indoor air temperatures at higher ambient temperatures (Nguyen, Schwartz, and Dockery 2014; Walikewitz et al. 2015). For each 1 K increase in outdoor temperature during the warmer periods, the average indoor temperature was found to increase between 0.29 and

Table 4. Evaluation of simulated temperature results for different thermal zoning methods using standard profiles and climate data from TRY.

Building, room	B1 bedroom			B2 bedroom			B3 living room			B4 living room			B5 bedroom		
Thermal zoning	BLD	APT	SZ	BLD	APT	SZ	BLD	APT	SZ	BLD	APT	SZ	BLD	APT	SZ
$DH_{+27°C}$ (Kh)	60	79	189	0	8	0	10	7	55	218	267	319	0	0	0
Min temp. (°C)	22.9	22.9	20.2	19.6	20.4	20.5	22.4	22.5	22.2	24.3	24.2	23.8	21.8	21.8	21.9
Max temp. (°C)	28.7	28.9	30.7	26.6	27.4	26.9	27.7	27.6	28.6	29.0	29.3	29.7	26.4	26.5	26.8
Avg. temp. (°C)	24.7	24.7	23.8	22.3	22.6	22.6	24.9	24.9	25.0	26.2	26.2	26.2	23.5	23.5	24.1
Avg. error, (%)		0.8	13.5		8.2	5.0		0.7	2.9		0.7	1.4		2.1	7.1
Avg. dif. (K)		0.1	1.1		0.7	0.4		0.1	0.2		0.1	0.1		0.2	0.6
Avg. bias (K)		0.0	1.5		0.7	0.4		0.0	0.1		0.0	0.0		0.0	0.5
Max. dif. (K)		0.5	2.8		3.5	3.7		0.3	2.5		0.5	1.3		0.6	1.6
CV(RMSE) (%)		0.0	6.0		3.0	1.8		0.0	0.6		0.0	0.1		0.2	2.0
MBE (%)		0.1	−3.5		1.1	1.3		0.2	0.6		0.2	0.1		−0.7	2.5

Code: BLD: whole building model; APT: apartment model; SZ: single-zone model.

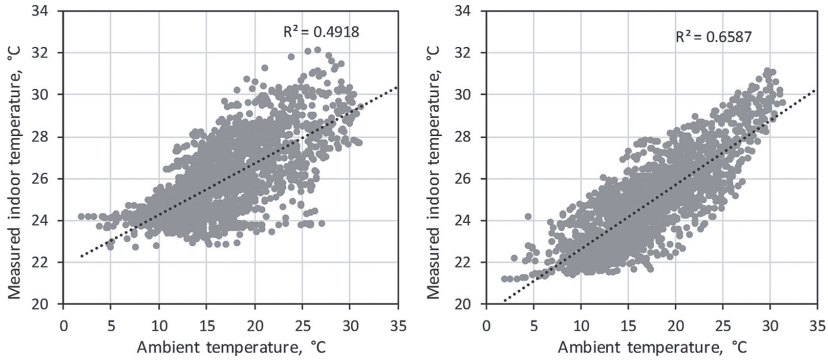


Figure 11. Correlation between measured hourly average indoor temperature and ambient temperature values during the three-month measurement period for two analysed rooms. Lowest linear correlation (left) was found for bedroom in building B1 and highest (right) for living room, building B3.

0.43 K (Tamerius et al. 2013; Nguyen and Dockery 2016). However, it must be stated that besides outdoor temperature, the main factors affecting indoor temperature are solar radiation, internal gains and occupant behaviour (Mavrogianni et al. 2014). Results from our field study are shown in Figure 11, where two measured cases are presented – with lowest and highest correlation of the sample between outdoor and indoor temperature.

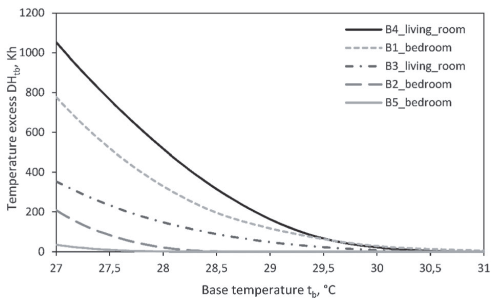


Figure 12. Measured temperature excess (DH) dependence on base temperature t_b in the analysed rooms during the summer period of 2014.

The measured DH for the studied rooms' dependence on the base temperature change is shown in Figure 12.

The simulation input parameters and variables, such as thermal properties of the building, climate data, heat gains and occupant behaviour, are the main source of uncertainty (Encinas and De Herde 2013; Taylor et al. 2014). Thus, the use of a safer, perhaps slightly overestimated approach in overheating assessment can be considered as justified.

The proposed equation, to act as a 'rule of thumb', for correcting the real year base temperature for DH calculations, to make measured room temperature values comparable to standardized calculations, is given as follows:

$$t_{b,n,\mathrm{corr}} = t_b + \frac{\mathrm{DH}_{t_b,n}}{105}, \tag{9}$$

where $t_{b,n,\mathrm{corr}}$ is the corrected base temperature for year n, t_b is the base temperature used in standardized calculations, $\mathrm{DH}_{tb,n}$ is the outdoor DH in degree-hours over the base temperature t_b for the measured year and the value 105 is the proposed constant with a reasonable safety factor accounting for the difference in climate data for a real year compared to TRY.

The example using the equation is presented in Figure 13. In the summer of 2014, the correction for base temperature is

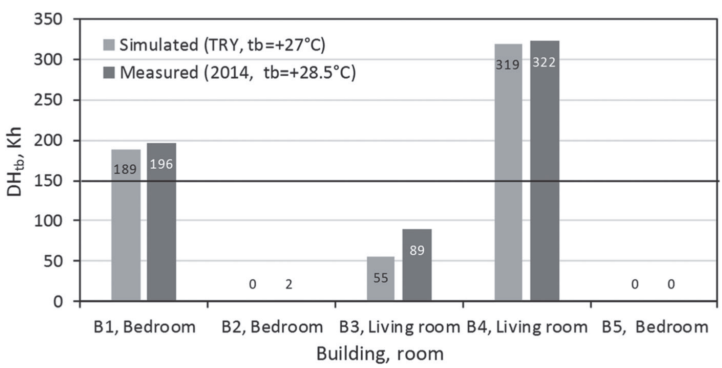


Figure 13. Comparison between measured temperature excess (DH) (summer of 2014) with corrected base temperature $t_b = +28.5$°C and simulated DH with base temperature $t_b = +27$°C. The 150 Kh line indicating the threshold for compliance.

1.5 K (for $t_b = +27°C$ and $DH_{+27°C,2014} = 157$ Kh) and the corrected base temperature $t_b = +28.5°C$. For all the cases, the corrected measured values are higher than the regulations-based simulated DH values.

4. Conclusions

In this study, we have compared three thermal zoning methods for summer thermal comfort assessment: two multi-zone approaches, modelling the whole building or apartment, and a single-zone approach, modelling only one room. Simulation results have been evaluated using CV(RMSE), MBE and average percentage error.

The average error increases with the decrease in model detail, thermal connections and air flow routes between neighbouring apartments and rooms. Although in some cases the change in statistical parameters seems low and acceptable in terms of overall indoor temperature prediction, the influence on excess temperature can be substantial, especially in small rooms with large glazing areas.

The analysis of the measurements and simulations reveals that the currently practised single-zone simulation method predicts overheating risk well . In the rooms where overheating was measured, the single-zone model provided the best agreement, indicating that the open doors' assumption of multi-zone model is always not valid in practice. However, as being sensitive for overheating risk estimation, for more accurate predictions, the single-zone method is typically overestimating overheating in the real situation, because it is not accounting the thermal dynamics of the building, heat dissipation between the zones, as well as has limitations in accounting, for example, cross-ventilation. Therefore, the apartment-based multi-zone method gave more realistic results, with little differences to the whole building approach, and can be suggested as an alternative method for more accurate simulations.

It needs to be emphasized that the Estonian single-zone method relies on ventilative cooling through buoyancy-driven window airing, and the fixed window opening position, defined in the regulation, gives sometimes room for interpretations in the design phase and is challenging for simulation tools as well. However, window airing seems to be compensating the oversensitivity of the single-zone model resulting in solid performance according to the measurements of this study.

Although overheating assessment by simulation is required by the state regulations as a precondition to apply building permit, these simulations have been done sometimes poorly. Coupled with the lack of resources, mainly in terms of state officials, and also competence to evaluate the quality and accuracy of the input and output data, the buildings are given permits and are being built with inevitable overheating problems. In such cases, it is extremely difficult for the tenant to prove the existence of the problem as it is defined only as a requirement and method evaluating building designs and not as an assessment for existing buildings. Using the proposed method, it is relatively easy to pre-assess an apartment or living space with only temperature measurements, without having to conduct simulations to prove the existence of overheating problems.

Although the buildings analysed in the current study represent well current construction practice, further research with larger sample representing a larger variety of buildings could be recommended.

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Publication III

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Daylight, Sunlight and Overheating Conflicts and Control with Shading Balconies in Residential Buildings

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Abstract

In modern low-energy residential buildings, solar heat gains contribute the most to the rise of indoor temperature during warm seasons. The use of balconies and overhangs as static shades can drastically reduce heat gains during summer. Such design can lower the risk of overheating and cut the need for active cooling systems, while still maintaining useful wintertime heat gains. Contrarily, the availability of direct sunlight throughout the year is considered mandatory and regulated in many countries as a requirement in building design. In Estonia, separate regulations govern requirements for daylighting and overheating prevention. The calculation methodology for insolation duration does not account for fixed external shades, making it difficult to fulfil. The colliding requirements leave little room for suitable, sustainable façade design options. We investigated the shading effect of balconies on summertime indoor temperatures, continuous solar insolation and daylighting. For the analysis we used dynamic simulation software IDA-ICE and standardized calculation methods. We covered the shortcomings of the methods and proposed a solution to assess the visual and thermal comfort indices without neglecting the use of static shading elements in building design.

Keywords: solar design, insolation, daylight factor, static shading, apartment buildings, thermal comfort; visual comfort

1 Introduction

Sustainable low-energy building design requires sophisticated analysis and cooperation between every party included in the process, starting from architects, energy efficiency specialists and HVAC engineers [1]. It is well-known that optimizing building performance to ensure low energy consumption must not compromise good indoor climate. Achieving balance between thermal and visual comfort is one of the key aspects, especially in free-running buildings, in terms of low heating energy need, low risk of overheating and sufficient direct sunlight as well as daylighting [2-4]. In moderate and cold climate countries, finding ways to maximize the utilization of solar heat gains during the heating season can benefit substantially in lowering the heating need [5-7]. However, the design implications considering mostly heating, such as the passive house standard, can result in unacceptably high indoor temperatures in warmer seasons [8-12]. With such trends in architecture and envelope design, namely the extensive usage of unshaded glazed façades and highly insulated airtight walls, the number of low energy buildings constructed with a tendency to overheat is increasing [13-15]. These cases occur not only in warm climates, but also in temperate and cold climate countries [12, 16-19]. Maivel, Kurnitski [16] investigated indoor temperature related problems in old and new apartment buildings in Estonia and found that overheating is most common in new buildings. With the combination of proper design of building elements and static shades, it is possible to assure comfortable indoor air temperature throughout the year and to avoid overheating in summer [20-24]. Most effective ways to avoid high indoor temperatures in free-running buildings have proven to be intensive ventilation and façade shading elements [25-27]. From the conventional shading devices, overhangs or light-shelfs can have the highest effect on solar heat gains reduction [28]. Regarding future climate scenarios, Porritt et al. [29] concluded that overheating could be avoided, amongst other passive means, with the use of external window shutters. Recent studies regarding overheating in new residential buildings have shown that most effective architectural shading elements are balconies, of which overhangs would provide sufficient shading for southern orientation and side-fins in western orientation [30].

Apart from energy efficiency and thermal comfort, urban planning and building designs should also account for overshadowing to assure sufficient daylighting and direct sunlight [31-33]. As natural light has a positive effect on occupants' comfort [34], it is emphasized as part of sustainable building design [35]. Daylight can be available from different sources: direct solar radiation, diffused by sky and clouds and reflected by the surroundings. Direct solar radiation is the most appreciated source of daylighting for its quantity, quality and distribution potential, especially for residential premises [36-38].

There are different methods to estimate both overheating risk [39-41] and daylighting performance [42-44] of buildings in the design phase. As most commonly acknowledged standardized methods only govern one or the other [45], it is also a common practice to analyse visual and thermal comfort assessment separately. Daylight is usually assessed by computer simulations or by mathematical models for simpler cases, such as single-room calculations. Recent studies have shown the importance of choosing a suitable daylighting design [42, 46-49] as well as a calculation method [42, 50, 51] by critically reviewing and comparing design principles, strengths and weaknesses of different ranges of daylighting systems, assessment methods and metrics. It is essential to ensure that excessive daylighting would not pose thermal discomfort to occupants [46]. In the European Union Member States, daylight requirements or recommendations mainly specify a minimum share of window or glazing area per floor area (WFR), indicate minimum levels for daylight or simply stipulate the need for sunlight access in buildings and a view to the outside [52]. Voll, De luca [53] have examined the Estonian building regulations on energy efficiency, daylighting and overheating prevention. The study concluded that in order to fulfil the requirements, especially in the light of low energy buildings, design options should be very carefully assessed. Aside from daylighting, estimating overheating risk is more complicated and in most cases, requires dynamic computer simulations [40, 54, 55]. Simson, Kurnitski [56] have concluded that room-based single-zone thermal modelling and simulation, as required in the Estonian building regulations, can be considered as an adequate approach in the initial building design phase.

In this study, we have analysed daylighting and summer thermal comfort of a modern apartment building in Estonia. The main focus is on static shading elements – balconies with opaque overhangs, railings and side-fins. We have conducted indoor temperature calculations according to the Estonian building regulations and daylighting assessment according to national and European standards. The aim of the study is to address the shortcomings of the calculation methods and to propose improvements to the current methodology for daylighting assessment considering summertime overheating prevention by the use of shading balconies.

2 Methods

2.1 Climatic conditions and sunlight availability

The study concentrates on buildings in Estonia, located roughly between latitudes 60º and 57º on northern hemisphere; with the capital, Tallinn, at 59.4ºN. Estonian climate is categorised as mild temperate, transitioning between maritime and continental. Hourly temperatures and global irradiation for every month from Test Reference Year (TRY)[57] are presented in Figure 1 to illustrate the climatic conditions. The TRY is constructed from selected weather data from 31 years and represents typical climatic conditions for the Estonian region.

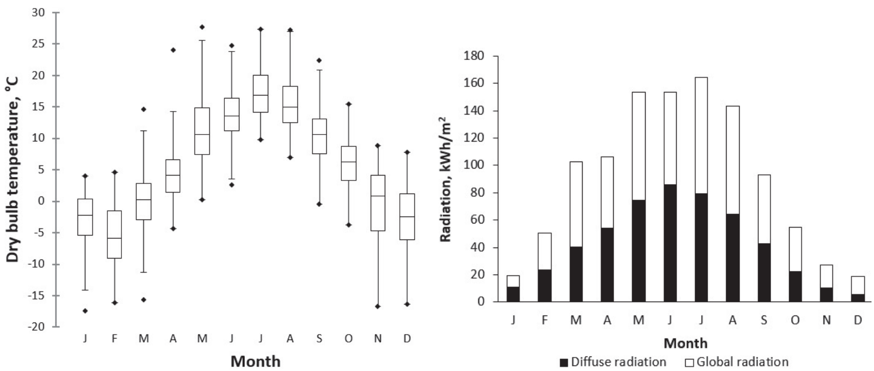


Figure 1. Hourly outdoor temperature distribution (left) and monthly solar radiation (right) in Estonia (data from TRY [57]).

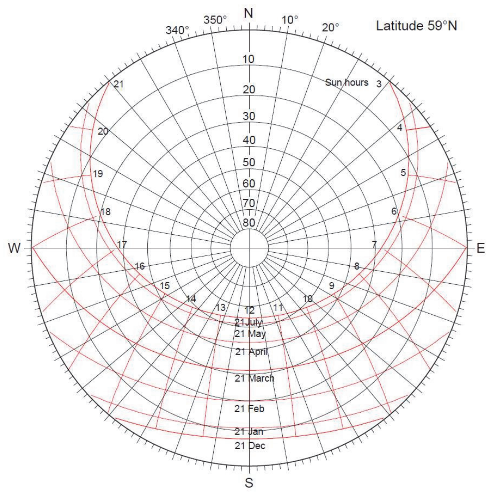


Figure 2. Sun path diagram for latitude 59°N (Tallinn, Estonia).

The climate throughout the land is fairly uniform, although slightly milder in the coastal areas. Spring and autumn days can be as hot as in midsummer, as sunny weather and warm air masses arriving from the south-east can drastically increase the temperature. Potential available sunlight during months, days and hours can be estimated from the sun path diagram for latitude 59ºN shown in Figure 2. Depending on the daytime duration and sky clearness, the sunshine duration during summer months is roughly ten times longer than in winter months [58]. Aside from Estonia, the same latitude region on which the results of the study can be applied, covers amongst others, parts of Sweden (e.g. Stockholm), Norway (e.g. Oslo), Finland (e.g. Helsinki), Russia (e.g. St. Petersburg), USA (e.g. Juneau, Alaska), etc.

2.2 Insolation requirements

The general dwelling requirements in Estonia stipulate that each living room, bedroom and kitchen must have at least one openable window, which provides an opportunity for airing and provides adequate natural lighting [59]. The specification of the natural light requirement is given in the standard EVS 894:2008/A2:2015 'Daylight in dwellings and offices' [60], which is a modified translation of the British standard BS 8206-2:2008 'Lighting for buildings. Code of practice for daylighting' [61].

Table 1. Insolation requirements for residential buildings [60].

No. of rooms in dwelling	Continuous insolation duration, h	Total insolation duration, h	Min. total insolation duration, h	
			Continuous	Intermittent
1	2.5	3.0	2.5	3.0
2 to 3	2.5 in one room 2.0 in two rooms	3.0 in one room	2.5/4.0	3.0
4 and more	2.5 in two rooms 2.0 in three rooms	3.0 in two rooms	5.0/6.0	6.0

The standard describes best design practice and sets out the criteria for which the requirements for adequate light can be considered fulfilled. According to the Estonian standard, all new residential buildings must be designed so that in dwellings with three or fewer rooms at least in one of the rooms continuous direct sunlight must be available minimum 2.5 hours a day throughout the period from April 22nd to August 22nd. In case existing surrounding environment does not permit the fulfilment of the latter requirement, a total minimum of 3h insolation is allowed during a day (Table 1).

In planning and designing new buildings, existing apartments should be provided with adequate insolation, with a reduction in the insolation duration not to exceed 50% of the initial total length in the room under consideration. Orientation of rooms and design of apertures in the building envelope should ensure sunlight duration of the evaluated interior. If the insolation of the apartment is insufficient, the insolation duration is not allowed and the increase is not obligatory. The observation point, on which the calculation is performed, is set the outer surface plane of the wall, in the middle of the window and 0.9 m above the floor of the room. Insolation can be considered effective if at least half of the surface of the window is in direct sunlight.

The European daylighting standard EN 17037:2019 'Daylight of buildings' [62] provides a 'minimum' of 1.5h, 'medium' 3h and 'high' >4h insolation duration periods. The main difference between EVS 894 and the proposed EN 17037 is that the EVS 894 introduces the insolation requirement for a period during the year and EN 17037 sets a design date. The calculations are to be made on spring equinox, March 21st, and compared to EVS 894, the observation point is set on the inner surface plane of the wall, in the middle of the window and at least 1.2 m above the room floor.

The reference point location for sunlight duration evaluation according to the daylight standards is presented as an example in Figure 3. Access to sunlight is determined if the reference point is insolated within the acceptance angle *αa* in plan. This acceptance angle is limited in the morning and afternoon by the azimuths of minimum solar altitudes *γs*. The sunlight duration shall be calculated by any reliable method that assumes the cloudless conditions and correct room orientation. Influence of various shapes of window linings and own exterior building constructions need to be accounted.

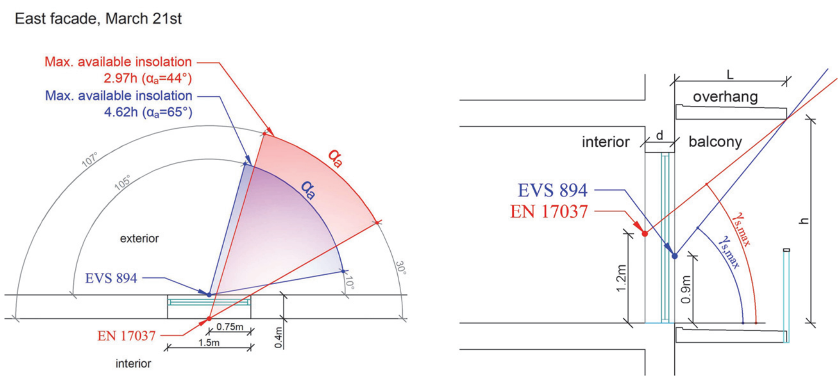


Figure 3. Sunlight availability assessment according to standards EN-17037:2019 [62] *and EVS 894:2008/A2:2015* [60]*: position of the observation point in plan (left) and in section (right) and its effect on insolation duration. The plan* (left) shows the available solar insolation duration for an east oriented 1.5m wide window for design day of March 21st. The section (right) shows the maximum possible solar altitude in case of a balcony overhang.

In case of window overhangs or balconies, to estimate the 'critical' depth of the overhang which would cast a shade on the reference point for insolation calculation (*γs,max* = 54.1° for Tallinn) according to the Estonian standard [60], the following equation can be used:

$$L_r = \frac{x-0.9}{\tan \gamma s{,}max} \qquad (1)$$

and in case of the European standard [62]:

$$L_r = \frac{x-1.2}{\tan \gamma s{,}max} - d, \qquad (2)$$

where L_r is the 'critical' depth of the overhang (m), x is overhang height from the floor (m), d is external wall thickness (m) and *γs,max* is solar altitude (Figure 3).

2.3 Daylighting requirements

The daylight standards give the following methods to assess minimum daylight provision to the interior [62]:

1) Calculation of daylight factors on the reference plane.
2) Calculation of indoor illuminances on the reference plane on a short time step (0.5 or 1 hour) using validated software and climatic data for the given site.

The European standard proposes values of target illuminances and minimum target illuminances to exceed 50% of daylight hours. The method will allow to confirm that the target illuminances and the minimum target illuminances are exceeded at least 50% of the time during the daylight hours. The calculation should fully take into account appropriate sky luminance for each time step, and handle light reflections on the external surroundings, window materials and components, internal reflections on indoor surfaces, and if appropriate or known, absorption by indoor furniture.

The average daylight intensity factor is used to characterize the light intensity from the sky. It is a good practice to ensure that the premises in residential buildings and in most other buildings are predominantly equipped with daylight. To achieve this, the average daily light intensity should be at least 2% [60]. Even if it is not necessary to achieve illumination, which has been resolved mainly in daylight, it is desirable that the average daylight intensity factor (aDF) in the dwellings should correspond at least to the values given in Table 2.

Table 2. Minimum values for the average daylight factor (aDF) [60].

Room	Minimum aDF, %
Bedroom	1
Living room	1.5
Kitchen	2

2.4 Overheating prevention requirements

Based on the European Union Directive 2010/31/EU [63], Estonian Government established requirements for overheating prevention for all new buildings in Estonia. The methodology to assess overheating risk in buildings is based on a static comfort criteria, limiting the maximum indoor temperature excess (DH) over a threshold temperature (t_b) [64]. The temperature excess is expressed in degree-hours (Kh) and calculated with the following equation:

$$\mathrm{DH}_{t_b} = \sum_{i=1}^{j} (t_i - t_b)^+ \qquad (1)$$

Where DH_{tb} is temperature excess (Kh) over the base temperature t_b (°C), t_i is the hourly mean room temperature and j is the total number of hours during the given period. When summing up degree-hours, only positive values are added to the sum, i.e. if $t_i > t_b$.

For residential buildings, the requirement is defined as hourly mean indoor temperature excess maximum limit of 150 Kh over a base temperature of t_b = +27°C during the summertime period from June 1st to August 31st, thus j = 2208. The equation (1) can be given as [64]:

$$\mathrm{DH}_{+27^\circ C} = \sum_{i=1}^{2208}(t_i - 27)^+ \quad (2)$$

The calculations include occupied hours only, which for residential buildings is the full period, including night time. A detailed procedure as well as requirements for calculation software are described in regulation no. 63 ‘Methodology for calculating the energy performance of buildings’ [64]. For the indoor temperature assessment, dynamic simulations are required for typical living rooms and bedrooms in the building that could experience overheating. The temperature excess / degree-hour methodology aims to express the severity of overheating and thus allows better insight on the possible problem than other static assessment methods and indices [65].

2.5 Studied building

The case study building is a seven-floor height concrete structured apartment building built in 2016 (Figure 4). The specification of the building envelope elements and parameters are gathered from the architectural design documentation. External walls are from reinforced concrete sandwich panels, with 200 mm mineral wool insulation in between the panels. The thermal transmittance of the walls is 0.17 W/(m^2·K). The height of the floors is 3m and room height of the apartments is 2.645m. The initial balconies were designed with a depth of 1.5m. Building envelope, systems and initial parameter values used in calculations are given in Table 3.

Figure 4. Rendered image (right) floor layout (right) of the studied building.

Table 3. Envelope and systems parameters of the building and initial input data used in simulations.

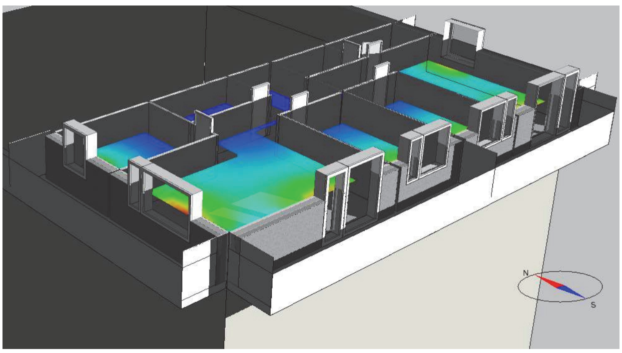
Parameter	Value	Unit
Building height		m
No. of floors	7	-
Air permeability q_{50}	3.0	m^3/(h·m^2 of ext. surf.)
Thermal transmittance:		
- External walls	0.17	W/(m^2·K)
- Roof	0.12	W/(m^2·K)
- Windows	1.1	W/(m^2·K)
- Window frame	2.0	W/(m^2·K)
Solar factor of windows (g-value)	0.4	-
Minimum allowed temperature (heating setpoint)	+21	°C
Ventilation airflow rate (outdoor air)	0.5	l/(s·m^2)
Internal heat gains (design):		
- Occupants (1.2 met, 28.3 m^2/Occ)	3.0	W/m^2
- Equipment	3.0	W/m^2
- Lighting	8.0	W/m^2

2.6 Simulations

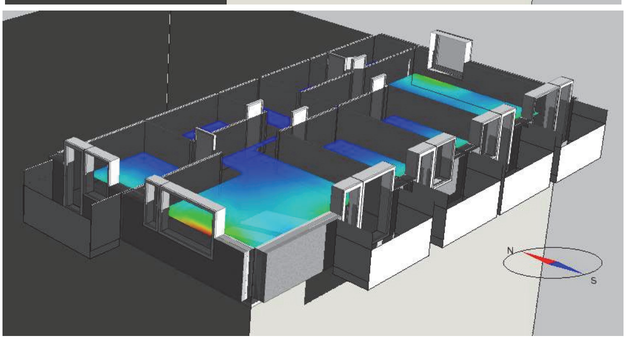
We used dynamic calculation software IDA Indoor Climate and Energy (ICE) v4.7.1 [66] to estimate hourly indoor temperatures, insolation duration and average daylight factors. This tool is well validated [67] and used in many studies regarding indoor climate [30, 56, 68] and energy consumption of buildings [53, 69-71]. The integrated daylighting analysis in IDA ICE is based on RADIANCE engine [72, 73], allowing precise zone illuminance and daylight factor calculations.

We studied in detail two apartments, one of which had south and east facing façades and the other south and west oriented façades. For the analysis we chose multiple façade layouts – different window combination and two options for balconies: full façade length (case 1) and separate for each room (case 2). The balconies were separated with opaque floor high side-fins, 3.0m apart, and guard rails with a height of 1.0m. The simulation models are shown in (Figure 5). The façade layouts for different windows and balcony doors were used to justify the balcony layouts. The studied window configuration variations are shown in Figure 6 and window parameters in Table 4. Balcony depth variations were 0.6m, 0.9m, 1.2m and 1.5m.

The national Building Code Act[74] requires for every living room, bedroom or kitchen to have at least one openable window. Thus also, the most commonly used measure to remove excess heat in dwellings is ventilative cooling trough openable windows. The latter occupant behaviour was simulated by implementing a temperature controller with a setpoint of 26.5°C at which the window was opened by the extent of the openable are fraction (Table 4).



(A)



(B)

Figure 5. Studied façade configurations: full façade length: case 1 (A) and separate balconies: case 2 (B).

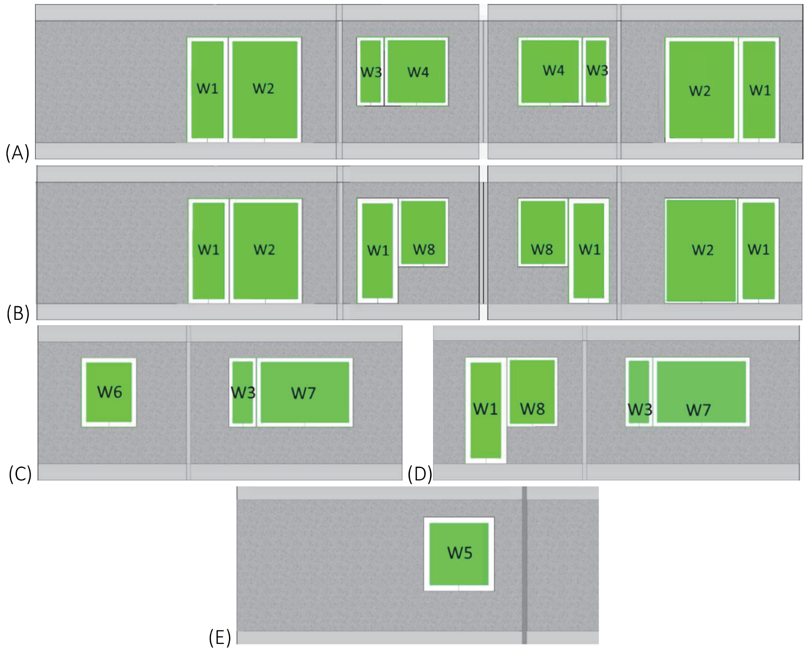


Figure 6. Window configuration cases for different façade orientations: south oriented full façade length balconies (A), south oriented separate balconies (B), west oriented full façade length balconies (C), west oriented separate balconies (D) and east oriented façade for both cases (E).

Table 4. Window parameters.

Code	Width x height, m	Frame fraction, %	Openable area fraction, %
W1	0.9x2.3	30	15
W2	1.6x2.3	20	-
W3	0.6x1.5	35	20
W4	1.4x1.5	20	-
W5	1.5x1.5	30	-
W6	1.2x1.5	30	-
W7	2.1x1.5	20	-
W8	1.1x1.5	20	-

Aside from natural ventilation using window airing, each apartment was modelled with mechanical supply-exhaust ventilation unit with a constant air flow rate of 0.5 $l/(s \cdot m^2)$ [75]. During the simulated summertime period, ventilation unit heat exchanger was set to by-pass regime, meaning that the supply air temperature was equal to the outdoor temperature.

Maximum internal heat loads from occupants, lighting and equipment were defined in the simulation models according to the national regulation [64] and are shown in Table 3 The heat loads were applied to every room as hourly profile based on typical dwelling usage rates as seen in Figure 7. Voll and Seinre [24] have found that a window to wall ratio (WWR) of 25–35% is the optimal ratio for a well day-lit standard office room, which in terms of daylighting can be applied also for living rooms. For the studied apartment configurations, the relevant parameters are shown in Table 5.

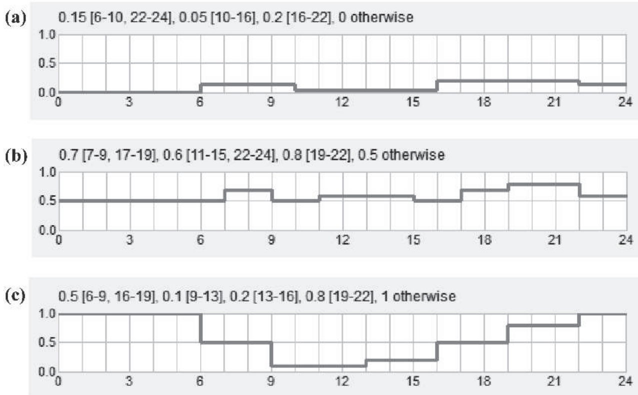


Figure 7. Internal heat gain profiles for lighting (a), equipment (b) and occupancy (c)[64].

Table 5. Room and window parameters for analysed cases.

	Room code*	Windows	Area, m^2				WWR,	WWR·g,	WFR,
			Floor	Windows	Glazing	Façade	-	-	-
Case 1	A1-BR1	W3+W4	12.6	3.0	2.27	7.4	0.30	0.12	0.18
	A1-LR	W1+W2; W5	28.32	8.0	5.97	26.5	0.22	0.09	0.21
	A2-BR1	W3+W4	13.25	3.0	2.27	7.9	0.29	0.11	0.17
	A2-BR2	W6	12.43	1.8	1.26	8.5	0.15	0.06	0.10
	A2-LR	W1+W2; W3+W7	41.4	9.8	7.50	29.5	0.25	0.10	0.18
Case 2	A1-BR1	W1+W4	12.6	4.2	3.13	7.4	0.42	0.17	0.25
	A1-LR	W1+W2; W5	28.32	8.0	5.97	26.5	0.22	0.09	0.21
	A2-BR1	W1+W4	13.25	4.2	3.13	7.9	0.40	0.16	0.24
	A2-BR2	W1+W8	12.43	3.7	2.77	8.5	0.33	0.13	0.22
	A2-LR	W1+W2; W3+W7	41.4	9.8	7.50	29.5	0.25	0.10	0.18

*Room code abbreviations: A - Apartment; B - Bedroom; LR - Living Room; WWR – window to wall ratio, g – solar factor, WFR – window to floor ratio.

3 Results and discussion

3.1 Insolation results

Figure 8 illustrates the differences in insolation duration calculation results for unshaded windows between the Estonian Standard [60] and the proposed European Standard [62] methods. Results are given for 21st of March and April. It is shown that the duration calculated according to Estonian Standard is 1.65h in March and 1.46h in April longer than according to the calculation results of the European Standard. As the European Standard has a minimum insulation duration of 1.5h, it is possible to guarantee the duration in March. Achieving 2.5h insolation is also possible in April, but the useful period according to the European Standard is 1.5h less.

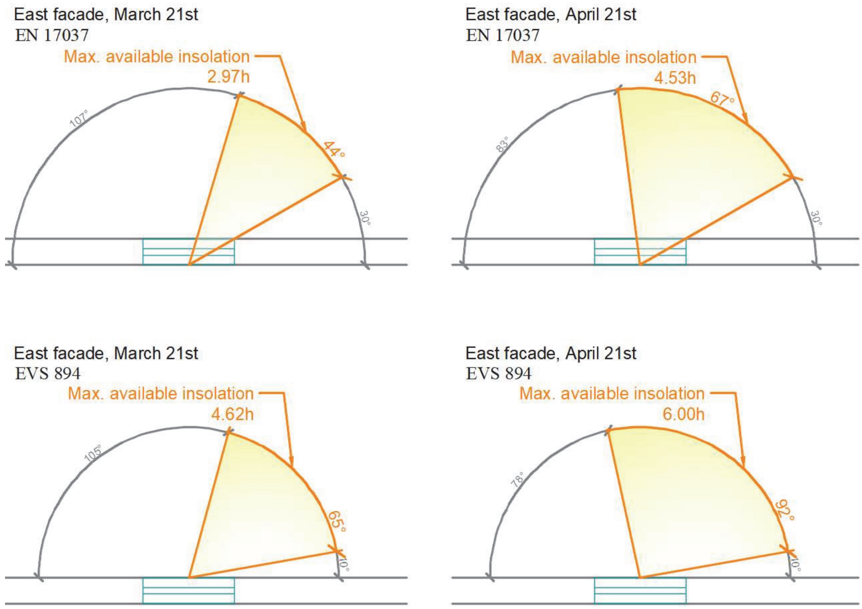


Figure 8. Comparison between maximum available insolation duration calculated according to EN 17037:2019 [62] (top) and EVS 894:2008/A2:2015 [60] (bottom).

In Figure 9 it is described the time at which the insolation begins and ends, the height angle and the duration of the insolation on the east and south oriented façades. In April and August, the Sun's trajectory is identical, so the altitude and azimuthal angles also coincide. The insolation duration of the eastern (and western) façades limits the sun's altitude in addition to the façade design.

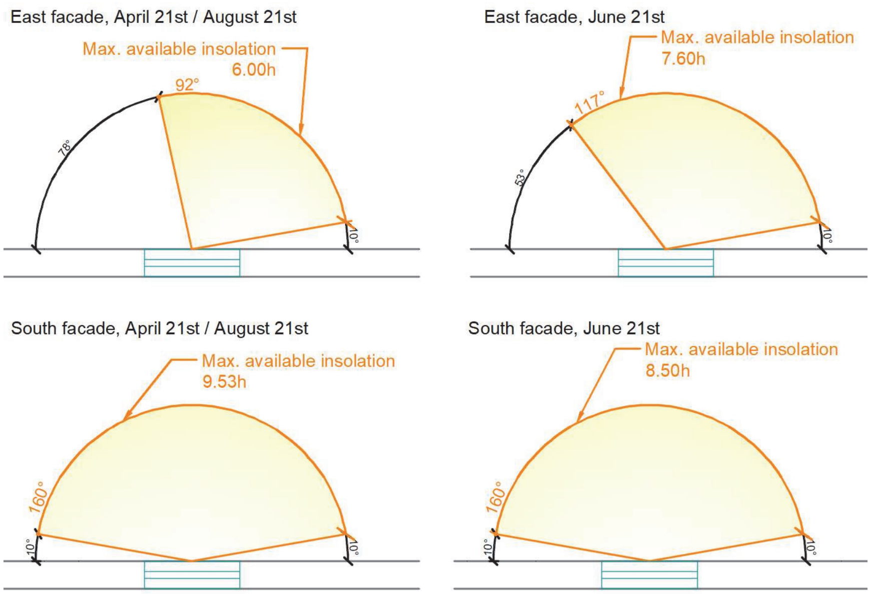
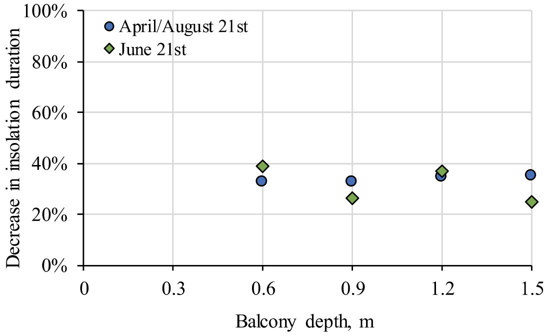
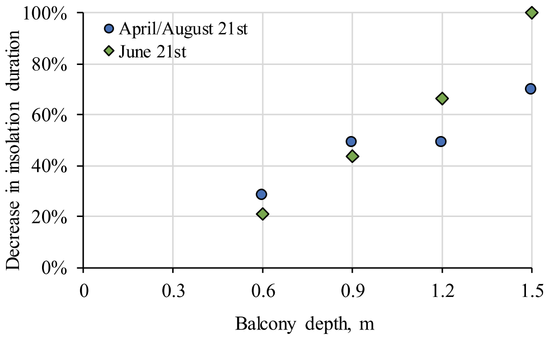


Figure 9. Maximum continuous insolation duration for east (top) and south (bottom) façade during spring/autumn and summer design days.



(A)



(B)

Figure 10. Average decrease of insolation duration for balcony depths up to 1.5m during April/August 21st and June 21st for eastern and western facade (A) and southern facade (B).

The east and west oriented façades have a minimum solar altitude of 6.0° in unshaded conditions. The maximum height angle differs from the maximum solar altitude for the south façade because the minimum solar altitude for the assessment is 10°.

The critical depth of overhanging balcony on the south façade windows, considering the height from floor to the balcony overhang of 2.74m, for April 21st and August 21st is L_r = 2.0m and for June 21st is L_r = 1.3m. The average decrease of insolation duration for different façades in April, August and June design days are shown in Figure 10. It is shown that the balconies reduce insolation time more in June than in April or August, as they obscure direct sunlight at high solar altitudes. The average insolation duration decreases with the increase in balcony depth. On average, a 0.6m deep balcony reduces insolation duration by 27%, 0.9m by 36%, 1.2m by 41% and 1.5m by 52%. In case of a 1.5m deep balcony, the decrease in insolation duration is on average 69%, but in case of south oriented façade, the decrease is 100%. These results pose a conflict between the requirements in daylight standards and national requirements regarding overheating prevention, making it difficult to achieve both sufficient insolation and minimize the risk of unacceptably high indoor temperatures in mostly south oriented facade cases.

Due to the early sunrise in June, the maximum insolation duration is available on the eastern and western façades in mid-summer. The change in the azimuth angle, which must guarantee 2.5h insolation on the eastern and western façades, is the same in April and June, as the range of azimuth angle increases. At the same time, the length of the insolation period on mid-summer on south facade is shorter than in April, and the required change in azimuth angle to ensure insolation is 2.5h is greater. The maximum elevation angles in south, east and west façades are higher in June than in April. Thus, it would be wise to determine the duration of insolation in April, based on the change in the azimuth angle necessary to ensure sufficient insolation duration.

3.2 Indoor temperatures

The indoor climate simulation results present clear correlation between balcony depth and room temperature, especially if window airing is not used. It can be seen, that even 0.6m balcony can reduce the maximum hourly temperature by 3.3K. Further reduction in maximal temperature is 3.5K/m and in median 2.0K/m with the increase of balcony depth. The median and mean temperatures for all cases for the simulation period were roughly the same, differing less than 0.1K. For unshaded conditions there is marginal difference in temperature distribution between bedrooms with south and west oriented windows. For south oriented windows, balcony depth has higher effect than for west orientation, indicating that in terms of shading, balcony design and selection of window parameters for western facades could require more careful analysis. Comparison between living room and bedroom temperatures reveal that the smaller-size bedrooms experience higher temperatures, especially in unshaded conditions. Furthermore, the effect of window airing can be substantial, especially when shading balconies are not used. The results for unshaded cases simulated with thermostat-controlled window opening macro show that the temperatures rise rapidly when direct solar radiation reaches the room and frequent window opening operation is required. In a realistic scenario the windows need to remain open during most part of the daytime. This indicates, that he ventilative cooling effect itself may not be sufficient to prevent rooms from overheating.

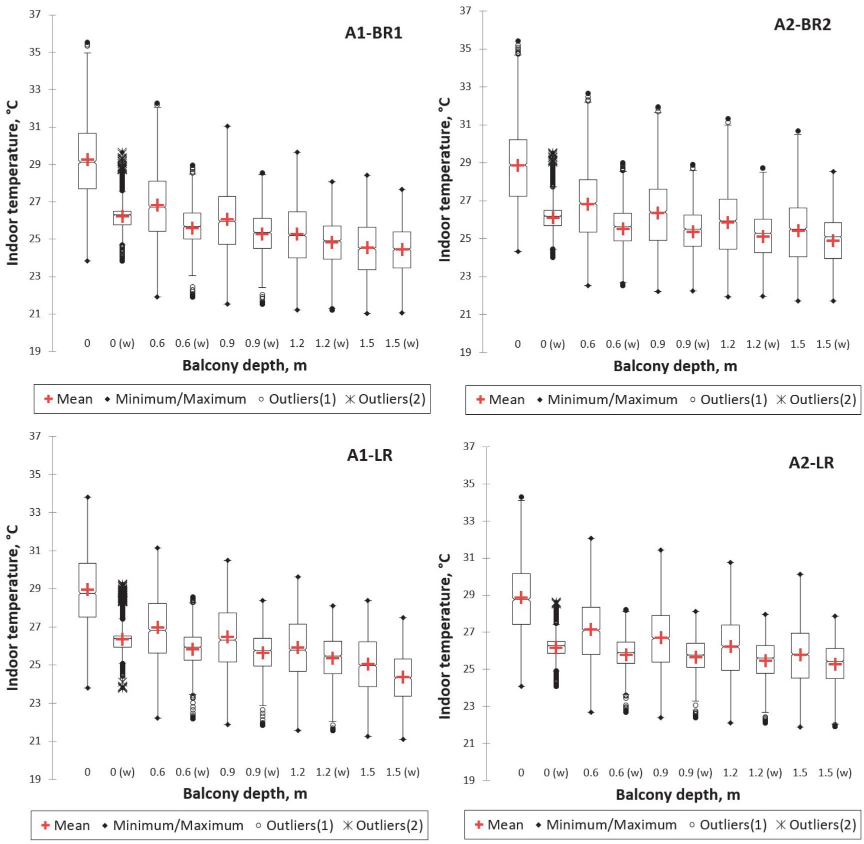


Figure 11. Simulated hourly indoor temperature distribution for different balcony depths in case of south (A1-BR) and west (A2-BR2) oriented bedrooms (top) and east/south (A1-LR) and south/west (A2-LR) oriented (bottom) living rooms without and with the use of window airing (w).

For the selected cases, the reduction in temperature maximums when using window airing was between 4.5K and 5.9K; and the median temperature was reduced by 2.4…2.8K. Therefore, the combination of both external shading and window airing is usually required to maintain lower room temperatures.

4 Insolation and overheating

Figure 12 shows that the decrease in the degree hours on the south facing rooms is more closely correlated with the insolation duration in June than in April or August (the insolation duration hours for April and August are identical).

Figure 12 illustrates the reduction in insolation duration and temperature excess for different depth balconies in case of south and west oriented bedrooms for the two balcony cases. It can be seen that the reduction of DH is in correlation with the insolation duration.

For south oriented rooms, a 0.6m deep balcony reduces the maximum possible insolation duration in April and August, by 1.75h in case 1, and 2.68h in case 2. For June 21st, the reduction is 1h48min for case 1 and 1.78h for case 2. The 0.6m deep balcony overhang causes 6.6% lower insolation duration during June 21st compared to the case without an overhang. Same depth balcony on April 21st reduces direct sunlight 5.3% for case 1 and 9% for case 2 compared to unshaded cases. From June 1st to August 31st the total direct solar radiation on the windows decreases with a 0.6m deep balcony 30.4% for case 1, resulting in 67% DH reduction. For case 2 a 0.6m deep balcony reduces direct solar radiation by 36%, resulting 71% in DH reduction. At the Insolation observation point, the difference in total solar radiation between the cases without shading and balcony variants is 6.1% for case 1, and 8.0% for case 2.

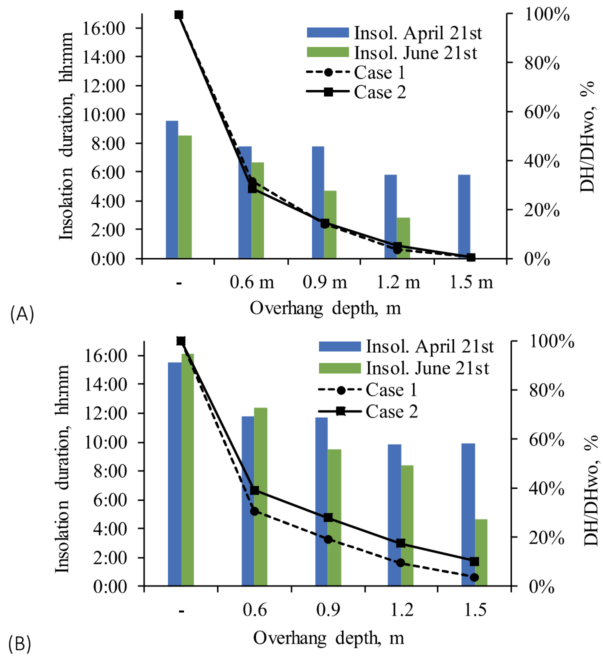


Figure 12. Continuous insolation duration for different depth balconies and DH relative to DH without balconies (DH_{wo}) for different balcony layouts (Case 1 and 2) in case of south (A) and west (B) oriented rooms.

4.1 Daylight factor

Calculations show that in order to ensure aDF ≥ 1.5% in the given bedroom, the visible sky angle should be at least 53 degrees. Adding a 1.2m balcony overhang, the required angle shifts 32 degrees towards the horizon (Figure 13). Achieving aDF ≥ 1.5% with a 1.2m overhang, the necessary angle of view of the visible sky is greater than the range of solar altitude required to ensure maximum insolation duration. In the determination of the insolation duration, the range of solar azimuth needs to be accounted as well. However, by ensuring aDF ≥ 1.5%, the range of solar altitude required for sufficient insolation duration (>2.5h) due to overhang shading is also ensured (42° for southern façade and 38° for eastern and western façades). The results for different rooms are shown in Table 6.

The calculation results show that the average daylight factor requirement for up to 1.2m deep balconies is met in most rooms. However, room A2-BR2 does not meet the criteria of aDF >1.5%, even in unobstructed case. With WWR 0.15 and WFR 0.10, the room also does not meet the dwelling window size requirements for WFR ≥ 1:8 [60]. In comparison, in case of A2-BR1, WFR is 0.14, which meets the requirement. For aDF > 1.0%, all rooms except A2-BR2 will meet the daylight requirements with 1.5m deep balconies. However, for different room configurations, daylight factor may decrease depending on the room plan, especially for rooms with one-sided windows.

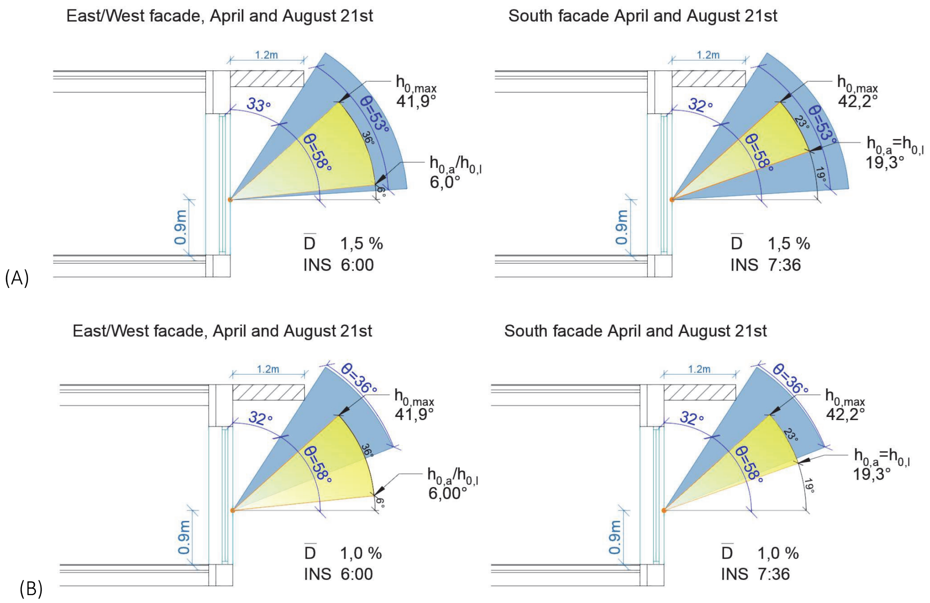


Figure 13. Available (blue area) and required (yellow area) azimuth angles for achieving aDF≥1.5% (A) and aDF≥1.0% (B) in east/west and south oriented rooms according to the methodology described in Estonian Standard EVS 894 [60].

Table 6. Average DF for different balcony overhang depths.

Balcony	Average daylight factor (aDF), %				
depth, m	w/o	0.6	0.9	1.2	1.5
A1-LR	**2.84**	**2.40**	**2.13**	**1.86**	**1.62**
A1-BR1	**2.11**	**1.92**	**1.71**	1.48	1.28
A2-LR	**2.56**	**2.25**	**1.99**	**1.76**	**1.56**
A2-BR2	1.43	1.32	1.18	1.02	0.87
A2-BR1	**2.07**	**1.95**	**1.75**	**1.50**	1.26

5 Conclusion

As long winters in temperate climate regions dominate the yearly cycle, allowing direct sunlight and increasing daylight availability during spring time in indoor spaces, specifically in dwellings is proven to have positive effect on occupant's wellbeing. However, during summertime the excess of solar radiation can cause indoor temperatures to rise uncontrollably and render the spaces uncomfortable or even unhealthy to occupy. In residential buildings, the issue is especially problematic in apartment buildings, where adaptation is more difficult than in private housing, e.g. in detached houses. Thus, limiting the external heat gains is necessary. Using balconies as shading elements can drastically reduce excess heat and decrease overheating. A balcony overhang with a depth of 0.6m decreases the temperature excess by two times and insolation duration about 27% compared to an unshaded window. Balcony with a depth of 1.2m, decreases the temperature excess 75% while still allowing enough exposure to sunlight although insolation duration is reduced roughly 41%. The reduction in simulated hourly room temperature maximum values was 3.5K/m and 2.0K/m in median values with the increase of balcony depth.

The average daylight factor is proven to be simpler to calculate and also correlates strongly with overheating calculation results in terms of temperature excess. Achieving the required values while using sufficient shading is easier than accounting for solar insolation.

The results of the study indicate that in the Estonian case, the minimum number of hours during which a room should receive direct sunlight should be proven for a reference day instead of a period of days. In addition, the requirements should allow more flexibility, especially for difficult cases, either shorter insolation duration periods or qualitative class-based assessment. It may be reasonable to establish rules for calculating insolation duration for rooms with balconies. During hot summer periods, allowing direct sunlight into rooms is not recommended, as it directly increases the risk of overheating. In most cases, assessing the average daylight factor values instead of insolation analysis would be sufficient and preferable to assess daylighting and allow reduce overheating risk. In special occasions and more difficult cases, insolation analysis may prove necessary. In these cases, it is recommended to apply insolation requirements only for spring months, e.g. for April, with lower elevation angles and azimuth angle averages equal to or less than one hour compared to summer months.

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Publication IV

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Overheating and daylighting evaluation for free-running classroom designs

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Abstract. Learning performance is strongly related to thermal comfort and lighting conditions of classrooms. Poor facade design can result in high indoor temperatures or insufficient access to natural light. To maintain the required temperatures and illuminance levels in such rooms may require intensive use of artificial lighting and active cooling systems, which are energy-intensive, costly to install, operate and maintain. The purpose of this study was to determine essential parameters and facade design options that ensure overheating prevention and fulfil daylight requirements in classrooms without mechanical cooling. The present study is based on simulations of a parametric room model with variable dimensions and orientations. Facade glazing solutions with optimal combination of solar factor and visible light transmittance were used to minimize overheating risk and maximize natural lighting impact. For east, south and west oriented facades, the effect of horizontal shading was also analysed. Overheating assessment through indoor temperature simulations was conducted with dynamic simulation software IDA ICE, daylighting was simulated with DIVA4 coupled with Grasshopper software. Results show that classrooms without mechanical cooling require in depth analysis to determine satisfying solutions for both overheating and daylighting criteria. The results of this paper can be used for early stage facade design guide for school buildings or similar use free-running buildings.

1. Introduction

The effects of indoor temperature and lighting conditions on schoolwork performance are relatively well researched [1-5]. Studies on lighting conditions show positive effects of natural light availability on performance and visual comfort [4]. Also, daylight utilization is an efficient way to save energy related to electric lighting [6] and heating [7], as its availability corresponds to the period during which buildings are occupied. Thus, daylighting is an important factor in classroom planning and school building design. At the same time excessive direct solar access can cause unwanted glare and solar heat gains that influence occupants' comfort and building energy use due to cooling need during warm periods [8]. Many studies have found, that higher indoor temperature has negative effect on thermal comfort and learning ability [2, 3, 9]. High indoor temperatures and overheating, specifically in temperate climate regions, are mostly recent problems, arising from paradigm shifts in architectural and energy efficiency related advances on building design [5, 10, 11]. It is essential to assess buildings in early stages of design development to properly ensure sufficient daylighting and prevent overheating.

In Estonia, daylight in building is regulated by the standard Daylight in dwelling and Offices [12]. The standard sets different minimum mean Daylight Factor (mDF) values for a series of internal spaces of buildings, of which classrooms are required to guarantee a minimum of 2% mDF. Overheating

assessment for new buildings in the design stage is required by the National Building Code by using temperature excess calculation method, based on dynamic indoor temperature simulations [13].
The present study investigates overheating and daylight performance of classroom and facade design variations for different floor dimensions, window sizes, glazing parameters and shading use. The scope was to find optimal solutions that fulfil daylight and overheating prevention requirements in Estonia.

2. Methods

We have analysed a classroom parametric model through computer simulations to assess indoor temperatures, overheating risk and daylighting. The parameters used in the simulation model creation are shown in Tables 1 and 2. The room model variations included different room widths and depths (5m, 6m, 7m, 8m and 9m) for a total of 25 room size and layout variations. The window layout was varied in accordance to the room width. For the room of 5m 2 windows of width and height 1.9x1.7m (Window-to-Wall-Ratio (WWR) 45.6%) were used, for the room width of 6m 3 windows of 1.466x1.7m (WWR 41.5%) were used, for the room width of 7m 3 windows of 1.8x1.7m (WWR 43.7%) were used, for the room of 8m width were used 4 windows of 1.45x1.7m (WWR 41.1%) and for the larger room width of 9m were used 4 windows of 1.7x1.7m (WWR 42.8%). The floor to ceiling height of the room is 3m for all the room variations. As a passive measure to reduce external heat gains from direct sunlight into the room, we used horizontal shading with a depth of 0.9m on top of the windows as an option for east, south and west orientations. Additionally, ground surface with 20% reflectance was modelled outside the room.

Table 1. Room and facade parameter combinations.

Room dimensions	Envelope	Windows	Window dimensions	Orien-tation	Glazing g-value	Glazing VT (%)	Shading depth (hor.)
Depth, m: 5, 6, 7, 8, 9 Width, m 5, 6, 7, 8, 9	Ext. wall: Concrete 150mm Exp.polystyr. 300mm Concrete 50mm U_{tot} 0,129W/(m²·K) Ext. window perimeter thermal bridge: 0.1W/(m·K) Fixed infiltration: 1.5m³/(h·m²)	Frame fraction 0.34 East/south/west: U_g 0.58W/(m²·K) U_{tot} 0.60W/(m²·K) East/west with shading: U_g 0.70W/(m²·K) U_{tot} 0.71W/(m²·K) North: U_g 0.61W/(m²·K) U_{tot} 0.62W/(m²·K) (north)	Recess depth 0.25m Room width, number of windows-width/height: 5m, 2-1.9/1.7m 6m, 3-1.466/1.7m 7m, 3-1.8/1.7m 8m, 4-1.45/1.7m 9m, 4-1.7/1.7m	E	0.35	0.635	-
					0.42	0.707	0.9m
				S	0.35	0.635	-
							0.9m
				W	0.35	0.635	-
					0.42	0.707	0.9m
				N	0.54	0.733	-

Table 2. Simulation input parameters.

Schedules		Internal gains		HVAC systems			Daylighting
Internal gains	Ventilation	Occupancy	Lighting / Equipment	Temp. setpoint	Supply air temperature	CAV air exchange	Reflectance values (%)
00:00-07:00 – 0.0 07:00-17:00 – 1.0 17:00-00:00 – 0.0	00:00-08:00 – 0.036 08:00-12:00 – 0.8 12:00-13:00 – 0.5 13:00-16:00 – 0.8 16:00-00:00 – 0.036	35W/m² 2.1m²/occ. 1.0 MET 0.85±0.25 CLO	5.0W/m² 12.0W/m²	+21°C … +25°C	>+16°C (without cooling)	4.2 l/(s·m²) idle 0.15 l/(s·m²)	Walls 50 Floor 20 Ceiling 70 Shading 35 Ground 20

2.1. *Overheating and indoor climate class assessment*

The overheating assessment was done according to Estonian Building Code regulations. Indoor temperature simulations were conducted with well validated building simulation software IDA ICE [14] (Figure 1). Hourly-mean indoor temperature values were used to calculate temperature excess (DH) over a set base temperature. The allowed cumulative temperature excess in case of classrooms is 100Kh and the base temperature 25°C. The simulation periods for school buildings are set from 1st of May to 15th of June and 15th of August to 30th of September. For outdoor climate input, Estonian test reference year is used, which is based on 30 year measurement data consisting of outdoor air temperature, relative humidity, wind velocity, direct and diffuse solar radiation [15].

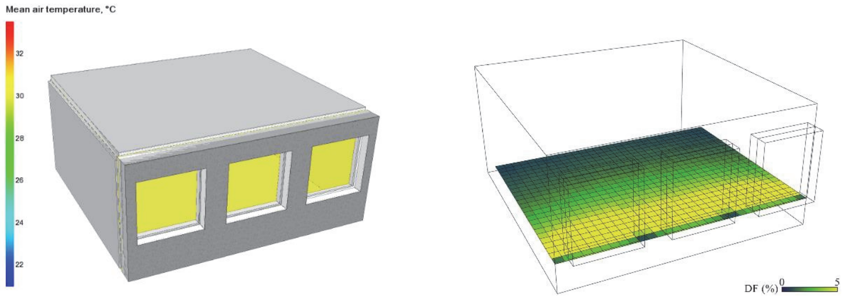

Figure 1. Examples of indoor temperature calculation model in IDA ICE (left) and daylight factor calculation model in Grasshopper using DIVA4 (right).

Aside from the overheating intensity assessment, we calculated the cumulative hours for the cooling period during which the room temperature was in bounds of specific thermal environment class according to the standard EVS-EN 15251 ‘Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics’ [16].

2.2. Daylight factor simulations

The parametric model of the classroom was built using the software Grasshopper for Rhinoceros and the analysis was carried out with daylighting design plug-in DIVA4 (Figure 1), which performs simulations through validated software Radiance [17]. Through the daylight analysis parametric model it is possible to assign reflectance (R) values to interior elements of the room (i.e. floor, wall, ceiling, external shading and ground) and visible transmittance (VT) values to the glazed surface of windows, set the simulation grid, select the simulation parameters, run the simulations and record result data. The R values used in the simulations were the same for all the classroom variations and are standard values recommended for Daylight Factor calculations, presented in Table 2. The daylight parametric model permits to associate in different ways the glazing VT values and use or not of the shading device. This procedure has been necessary to match the room variation parameters used for energy efficiency studies. Different combinations of glazing VT and use of shading has been used for the different orientations in consideration of Estonian overheating requirements. Because Daylight Factor analysis do not take into account windows orientation, daylight simulation combinations refer solely to glazing VT and use of shading. The combinations are presented in Table 1. The grid used for the simulation has a size of 0.2m, was located at 0.75m from the floor and occupies 80% of the floor area. The main Radiance parameters used in the simulations are: -aa .1 -ab 5 -ad 1024 –ar 256. As required for DF simulation the CIE overcast sky model was used. The Daylight Factor simulations were performed automatically for all the classroom size and parameters variations through an automation function of the parametric model and the values of mDF were recorded for each iteration.

3. Results and discussion

Results of overheating and daylight factor are presented for different orientations due to the different glazing g-value, VT and shading described in methods section. For each orientation a figure is composed, how rooms with different WFR and dimensions respond to requirements studied. Rooms are ordered by the decreasing value of WFR, cumulative time is shown firstly, overheating secondly and daylight factor results thirdly. The color-coded cumulative graph shows duration in percentages during which the hourly room temperature values stayed between the limits of a specific indoor climate class (IC), ranked from I (best) to IV (worst) according to the standard [16]. Overheating hours and mean daylight factor values are marked as green squares, if both criteria are met and as red if one or both of

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the criteria do not meet the requirements. Room result figures are divided to left and right by shading use.

For east orientation (Figure 2) rooms without shading and with WFR over 0.23 are overheated and rooms with width of 5m also do not meet the overheating requirement. Same rooms gain 1 to 2% more time out of II IC class compared to rooms, which stay below 100Kh line. All the rooms without shading are well lighted as mDF is over 2%. It is seen, that as the WFR increases and floor plan has more width and less depth, classrooms are both more naturally lighted and overheated. If shading is added and glass g-value increases from 0.35 to 0.42, room air temperature hours in III and IV IC class decrease up to 3%. Most of the rooms are underneath the overheating requirement line, only half of the rooms meeting the daylight factor criteria. Only 6 rooms, compared to 10 in the initial situation, of 25 met both criteria.

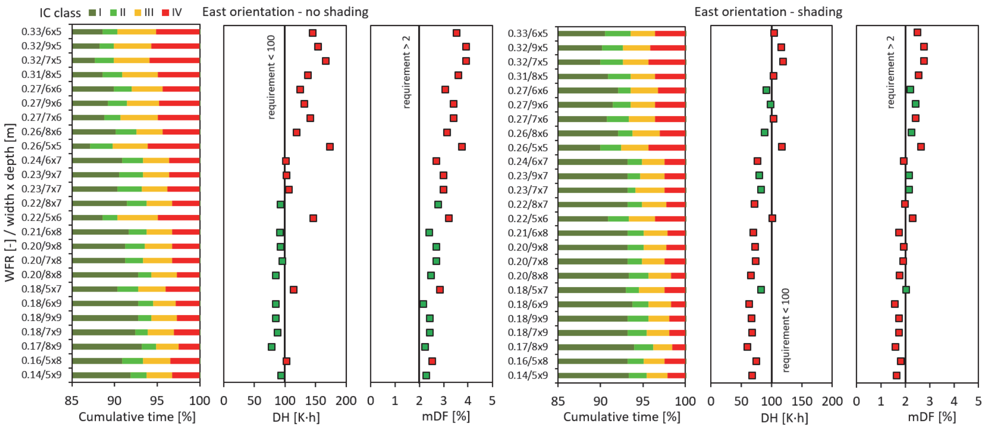

Figure 2 Simulation results for east oriented classrooms: indoor climate class (IC) cumulative time during cooling period, temperature excess (DH) and mean daylight factor (mDF) without (left) and with (right) shading.

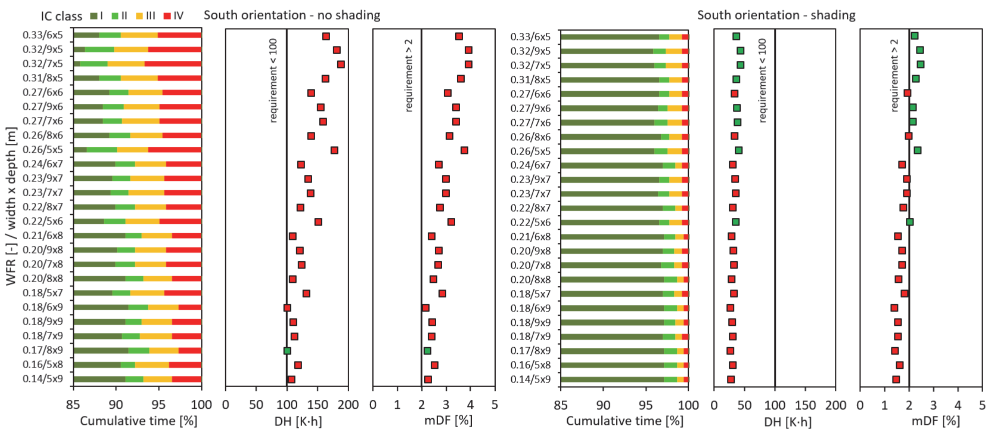

Figure 3 Simulation results for south oriented classrooms: indoor climate class (IC) cumulative time during cooling period, temperature excess (DH) and mean daylight factor (mDF) without (left) and with (right) shading.

In south orientation (Figure 3) without shading all rooms basically are overheated and properly naturally lit. Up to 10% of the time, air temperature in classrooms does not meet II IC class. After adding shading, only 2 to 3% of the time room air temperature is out of II IC class. While all the rooms now meet the overheating criteria, only 8 rooms of 25 have mDF over 2%.

For west orientation (Figure 4) 20 of 25 rooms meet both criteria without cooling, while room air temperature varies from 5 to 8% out of II IC class. Adding horizontal shading and optimized g-value of 0.42 similarly to east, all the rooms are underneath the overheating criteria, while 13 rooms with higher WFR do not meet daylight criteria. Classroom air temperatures IC classes for being out of II class also decreases between 3 to 5% of the time.

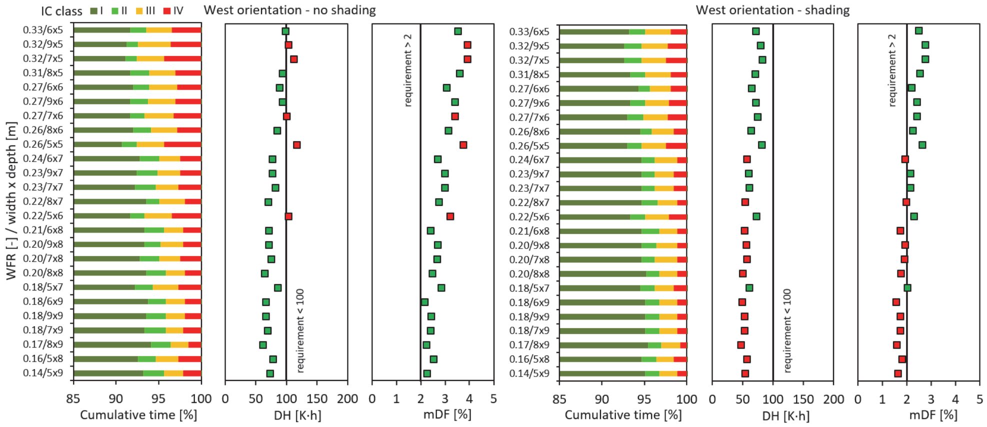

Figure 4 Simulation results for west oriented classrooms: indoor climate class (IC) cumulative time during cooling period, temperature excess (DH) and mean daylight factor (mDF) without (left) and with (right) shading.

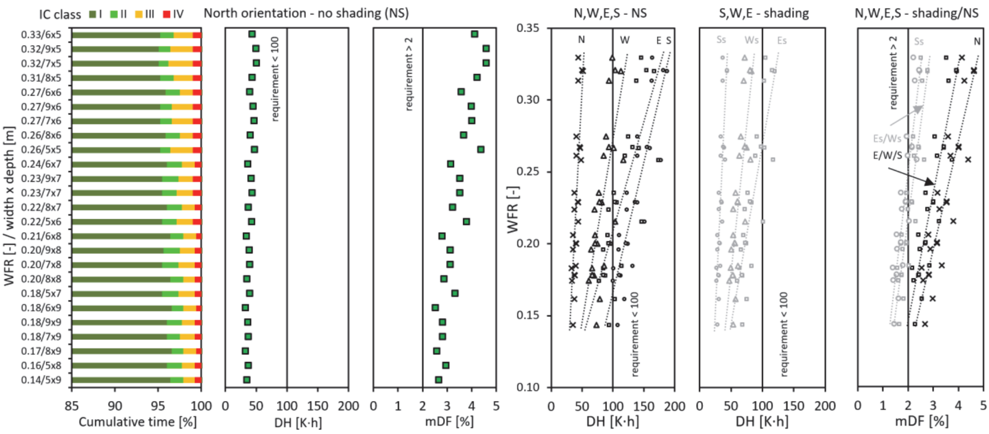

Figure 5 Simulation results for north oriented classrooms: indoor climate class (IC) cumulative time during cooling period, temperature excess (DH) and mean daylight factor (mDF) without shading (left) and for all facades, WFR correlation with DH and mDF (right).

As it is unnecessary to block direct sunlight on north façade (Figure 5), room results are presented only for the initial situation without shading. It is seen by the green squares that all the rooms meet both overheating and daylight factor criteria. Rooms with higher WFR have 1 to 2% more cumulative hours out of II IC class. Room DH values are more constant compared to higher mDF as the WFR increases.

For east, south and west orientations, rooms with wider width and shorter depth dimensions received more daylight. For north oriented facade, all the analysed cases fulfilled the overheating and daylight requirements. IC class percentages indicate that room air temperature is mainly affected by internal gains of students, electrical equipment, lighting and supply air. Results are shaped less from the direct sunlight and as the WFR increases, more diffuse lighting enters the room. Similar distribution of results is seen on south façade with shading, but the balance gap between DH and mDF is clearly smaller for maintaining both criteria requirements. On the east and west façade results are more spread out, but still parallel as WFR increases. The room air temperature is less time out of II IC class for all south, east and west orientations if shading is added to the windows of the classrooms. Right side of Figure 5 with all the facades and simulated classrooms together shows why DH and mDF should be calculated together during the building design process.

4. Conclusion

The aim of this study is to determine whether the school building classrooms could be designed without active room cooling units and cooled ventilation supply air. Passive cooling methods, like decreasing window glass g-value and external shading decrease the amount of sunlight into the rooms, may cause poorly conditions for natural lighting as a result. Therefore, both overheating and daylight parameters must be analysed jointly. Results show that as window-to-floor ratio increases, the room receives more daylight but also becomes more vulnerable to temperature rise and overheating. In the other hand, with increasing depth, overheating risk lowers and daylight level decreases.

Parametric study shows that horizontal shading is more helpful on the southern façade. Adding shading to eastern and western facades with modified window parameters, distribution of classrooms meeting both temperature excess and mean daylight factor requirement changes and for west it also decreases. The easiest balance between two criteria is on the north façade due to low amount of direct sunlight. Adding shading reduces the number of hours out of indoor climate class II, while temperature excess method illustrates more efficiently the intensity of overheating. In addition, temperature excess overheating method results correlates well with daylight result distribution.

Designing low-energy school buildings without active room cooling units or cooled mechanical supply air ventilation, facade design is critical to ensure thermal comfort and lighting conditions that directly affect students' performance. As school buildings are not used during summertime, it is possible to design classrooms to meet both overheating and daylighting requirements without the need for mechanical cooling systems. However, proper design requires skillful analysis of suitable combination of room dimensions, window sizes, glazing parameters and shading options to meet both overheating and daylight requirements.

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Publication V

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Evaluating Daylight Factor Standard through Climate Based Daylight Simulations and Overheating Regulations in Estonia

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Abstract

Building interiors daylighting is a crucial aspect for occupant comfort and energy efficiency. Standards and requirements exist to guarantee minimum levels of natural illumination in new buildings on the basis of different metrics. Some rely only on interiors static characteristics, others additionally take into account location climate. The main aim of the present study is to investigate the validity of the static Daylight Factor (DF) requirement of the Estonian daylight standard against more reliable climate-based daylight simulations using the approved method Spatial Daylight Autonomy. Results show the weakness of DF in predicting appropriate daylight availability of building interiors for the city of Tallinn. Evaluations of DF in relation to overheating regulation is also presented.

Introduction

Daylight is the most appreciated source of illumination for building interiors of every typology for its capacity to render surfaces and objects without altering colours, to create contrasts which generate architecture quality and to be diffused in depth into the floor plan (Johnsen and Watkins, 2010). In commercial, office or school buildings daylight is particularly useful because its availability mostly coincides with the hours during which buildings are used (Reinhart, 2014). Additionally, daylight variability during days and seasons and day-night cycles improve well-being of occupants and their circadian rhythm (Lockley, 2009). In schools, the use of daylight through windows and skylight proved to be associated with improved student learning performances (Heschong, 2002). Window to Wall Ratio of minimum 20% proved to be the most significant daylight feature in school buildings for the improvement of student tests performance (Annesi and Annesi-Maesano, 2016).

Different methodologies exist to predict building interiors daylight levels, such as use of models and formulas or more reliable computer simulations (Reinhart and Lo Verso, 2010). Daylight Factor (DF) is a long-standing metric which estimates the potential natural illumination of an interior point as a percentage of the illuminance of an unobstructed point on the exterior of the room (Waldram, 1923). DF takes into account room size and layout, windows size and position, external obstructions, materials reflectance and glazing transparency. DF is an efficient metric due to its simple calculation method fast to perform through computer simulations. The limitation of DF calculation lies in not taking into account building location climate and orientation. In recent years researchers developed new climate based annual daylight metrics to predict accurately the quantity of illuminance and daylight autonomy in relation to threshold values (Reinhart et al., 2006; Nabil and Mardaljevic, 2006). Spatial Daylight Autonomy (sDA) is a recently developed climate-based metric used for the evaluation of daylight potentiality of different workplace environments such as offices and classrooms through dynamic simulations (Illuminating Engineering Society, 2013). sDA, taking into account location climate and room window orientation in addition to all the parameters used by DF, estimates the floor area ratio of a room that will receive, solely by daylight, the minimum illuminance required for at least 50% of the operating hours during the entire year. Together with sDA, Annual Sunlight Exposure (ASE) metric is defined. ASE estimates the floor area ratio which exceeds fixed amount of illuminance and operating hours during the entire year. The maximum floor area ratio allowed by ASE is 10%. ASE is introduced to balance daylight availability and risk of glare in case of excessive direct solar access of building interiors.

In Estonia the standard “Daylight in dwellings and offices“ set the required daylight in interiors using minimum mean Daylight Factor (mDF) values for different building typologies (Estonian Centre for Standardization, 2015). For school classroom it is required an mDF of minimum 2%. Though being positive for occupant comfort daylight can generate solar gains that harm building energy efficiency due to increased cooling energy demand also at northern latitudes (Voll et al., 2016a). To improve building energy efficiency the Estonian regulation “Minimum Requirements for Energy Performance” sets the maximum internal temperature in degree-hour that different typology of buildings cannot exceed for different periods of the year (Estonian Government, 2019a). Recent developed studies investigate the relation of the two conflicting regulations and develop optimal solutions for building envelope and urban design (De Luca et al., 2018; Voll et al., 2016b).

The present study investigates if the minimum quantity of mDF 2% required by the Estonian standard guarantees proper level of interiors daylight through climate-based simulations, using the metric sDA. At the same time overheating analysis is performed to evaluate the relation between daylight standard and energy efficiency requirements in Estonia, together with ASE analysis for glare risk potentialities. The research presents an original contribution inasmuch still few studies evaluate reliability of DF metric and none yet in relation to Estonian climate and regulations. The present study is part of a larger research about design methodologies for school buildings in Estonia, thus school classroom is used as room type for the case study.

Methods

The single-sided window classroom model has a height of 3m and a wall thickness of 0.5m (Figure 1). A large number of classroom variations are generated through a parametric model. The room variations are different for width and depth, number and size of windows, orientations, window glass Visible Transmittance (VT), and presence of shading.

Room parametric model

The parametric model combines all the room depths, widths and orientations on the basis of 2 room types different for glazing Visible Transmittance and use of shading, excluding same combinations of north orientation for a total of 175 (Table 1).

Table 1: Room parameters used in simulations.

Type	Room d (m)	Room w (m)	Orien tation	Glazing VT(%)	Shading 0.9m
1	5	5	South	0.635	No
	6	6	East	0.635	No
	7	7	North	0.733	No
	8	8	West	0.635	No
	9	9			
2	5	5	South	0.635	Yes
	6	6	East	0.707	Yes
	7	7	North	0.733	No
	8	8	West	0.707	Yes
	9	9			

Same room sizes for depth and width are used. The widths of 5m, 6m, 7m, 8m and 9m are characterized by different quantity and size of windows, respectively by 2 of width and height 1.9x1.7m (WWR 45.6%), 3 of 1.466x1.7m (WWR 41.5%), 3 of 1.8x1.7m (WWR 43.7%), 4 of 1.45x1.7m (WWR 41.1%) and 4 of 1.7x1.7m (WWR 42.8%). VT values and shading are assigned selectively to the room combinations for depth, width, and orientation with the scope to obtain classrooms which fulfil the Estonian maximum internal temperature requirement (Figure 2).

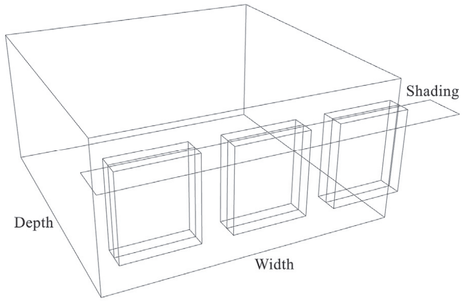

Figure 1: Room used in the study.

Windows have frame size of 5cm except the operable one with frame of 15cm. The shading is a single horizontal element located 10cm above the windows. The parametric model, realized through the software Grasshopper for Rhinoceros (McNeel, 2019), integrates room parametric model with daylight analysis model and automation tool to run all the room variation simulations automatically and export result data.

Daylight Factor analysis model

Reflectance (R) values are assigned to the elements of the parametric model walls, floor, ceiling and shading. For interiors daylight assessment regulations recommend standard conservative reflectance values. In addition, for the present study improved reflectance values are also used to obtain a larger number of combinations, for a total of 350, and perform simulations using real case reflectance parameters (Table 2). No surrounding buildings are modeled due to open areas locations of majority of new schools. The presented glazing VT values are used in the DF model.

Table 2: Standard/improved material reflectance values.

	Walls	Floor	Ceiling	Shading	Ground
R	50/70	20/40	70/80	35	20

The validated daylight simulation software used is Radiance (Ward, 1994). The simulation grid is made of 20cm cells for 80% of the floor, i.e. the regularly occupied area as suggested by BREEAM and LEED, and is located at 0.75m height (Figure 3 and 4). The main Radiance parameters used are: -aa .1 -ab 5 -ad 1024 –ar 256. The CIE overcast sky model is used in the simulations.

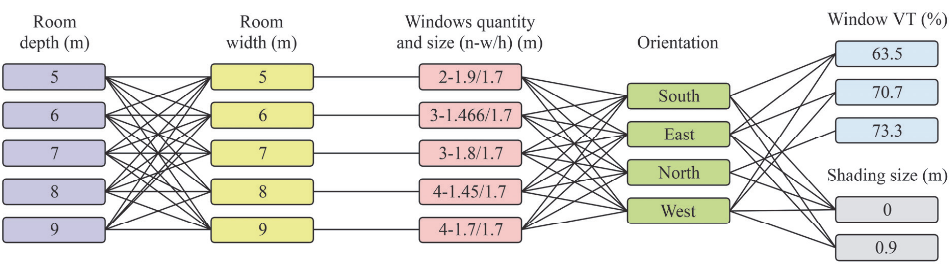

Figure 2: Diagram of room parameter combinations.

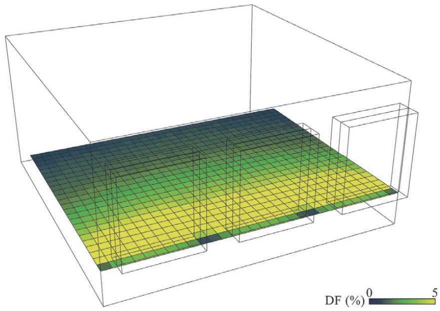

Figure 3: Room with Daylight Factor analysis grid.

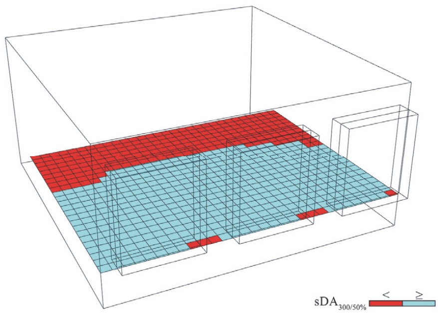

Figure 4: Room with Spatial Daylight Autonomy grid.

Daylight annual climate-based simulation model

The parametric model provides room elements different for every variation. Daylight annual dynamic simulation model uses the same reflectance (R) and Visible Transmittance (VT) values as Daylight Factor analysis.

Statistical weather data of the city of Tallinn from epw (EnergyPlusWeather) file 260380-TALLIN-HARKU--2014 are used. Annual daylight simulations are performed using the software Daysim that iterates Radiance simulations using daylight coefficients for a variety of sky conditions on the basis of the statistical weather data (Reinhart and Walkenhorst 2001). The occupancy schedule used is school year (01.09-15.06) Monday to Friday 8am-4pm. The output of annual dynamic simulations is the daylight autonomy, i.e. the percentage of time during which the interior required illuminance is provided by daylight, using different metrics.

For the present study the sDA and ASE thresholds used are those of the approved method IES LM-83-12 (Illuminating Engineering Society, 2013). The room is considered well daylit if at least 55% of regularly occupied area receive 300lx for at least 50% of operating hours ($sDA_{300/50\%}$) (Figure 4), and if no more than 10% receives 1000lx for more than 250 hours ($ASE_{1000,250}$).

Daylight Factor and annual climate-based simulations are integrated in the parametric model through DIVA4, a Grasshopper environmental and daylight design plug-in (Solemma, 2019).

Overheating simulation model

Dynamic simulation software IDA-ICE v4.8 for overheating calculations is used (EQUA, 2019). Key parameters for simulations are given in Table 3 to 5 (Estonian Government, 2019b). Educational building maximum overheating is 100 °C·h for test period 1st of May-15th of June and 15th of August-30th of September.

Table 3. Envelope & thermal comfort parameter values.

Parameter	Value
External wall (precast concrete element)	Concrete 150 mm Exp. polystyrene 300 mm Concrete 50 mm U_{total} 0,129 [W/(m²·K)]
Windows – no shading	g 0.35; U_g 0.58 [W/(m²·K)]; U_{total} 0.60 [W/(m²·K)]; frame rate 0.034 (east, west, south) g – 0.54; U_g – 0.61 [W/(m²·K)]; U_{total} – 0.62 [W/(m²·K)]; frame rate 0.034 (north)
Windows – shading	g 0.42; U_g 0.70 [W/(m²·K)]; U_{total} 0.71 [W/(m²·K)]; frame rate 0.034 (east, west)
External windows perimeter thermal bridge	0.1 [W/(m·K)]
Fixed infiltration	1.5 $m^3/(h{\cdot}m^{2,\text{external surface}})$
Heating setpoint	+21 (°C)
Cooling setpoint	+25 (°C)
Supply air temperature	>+16 (°C) (without cooling)
Air exchange rate	4.2 [l/(s·m²)], CAV

Table 4. Internal heat gains values.

Internal heat gains	Value
Occupant	14.0 (W/m²) Activity level 1.0 (MET) Clothing 0.85 ±0.25 (CLO)
Lighting	5.0 (W/m²)
Equipment	12.0 (W/m²)

Table 5. Time schedule rules.

Schedule	Rule (smoothing factor 0)
Ventilation	00:00-07:00 – 0.0 07:00-17:00 – 1.0 17:00-00:00 – 0.0
Internal gains	00:00-08:00 – 0.0 08:00-12:00 – 0.8 12:00-13:00 – 0.5 13:00-16:00 – 0.8 16:00-00:00 – 1.0

Results

Daylight and overheating simulation results are presented. Daylight simulation results are used to evaluate through reliable dynamic annual daylight simulations if the minimum mDF of 2% required by the Estonian standard guarantees adequate interiors illuminance. Overheating simulation results are used to evaluate relation of mDF values and the Estonian interior temperature requirement.

Daylight Factor simulation results

Being Daylight Factor not dependent on room orientation, results are grouped for cases with same glazing VT and use of shading. All room variations without shading fulfil the mean Daylight Factor ≥ 2% requirement. Minimum and maximum values are presented in Table 6.

For variations with shading, with VT 63.5% (south) and with standard materials mDF requirement is fulfilled by all variations with room depth 5m and by variations 5x6m, 7x6m and 9x6m (width x depth). With improved reflectance materials mDF is fulfilled by all variations with depth 5m, 6m, 7m, 8m except 6x8m and 8x8m, and 9m. For variations with VT 70.7% (east and west) and standard materials mDF is fulfilled by all variations with room depth 5m, 6m, and 7m except cases 6x7m and 8x7m. With improved reflectance materials mDF is fulfilled by all variations except 6x9m.

Table 6: Min. and max. mDF values. (size width x depth)

	VT (%)	Stand. materials		Imp. ref. materials	
		Min	Max	Min	Max
No shading	**63.5 (s-e-w)**	2.16% 6x9m	3.93% 7x5m	2.7% 6x9m	4.91% 7x5m
	73.3 (n)	2.54% 6x9m	4.61% 9x5m	3.16% 6x9m	5.64% 7x5m
Shading	**63.5 (s)**	1.42% 8x9m	2.46% 7x5m	1.74% 6x9m	3.07% 9x5m
	70.7 (e-w)	1.56% 6x9m	2.77% 7x5m	1.98% 6x9m	3.45% 9x5m

Spatial Daylight Autonomy simulation results

Simulation results of sDA are presented and relation with mDF results is analysed. mDF results are presented for different orientations due to different glazing VT and shading combinations, as discussed in section Room parametric model, and to analyse relation with sDA.

For south orientation all 50 room variations without shading device fulfil sDA requirement (Figure 5). For room with standard materials sDA varies from 61% of variation 7x9m to 99.9% of variation 6x5m, 7x5m and 8x5m. Using improved reflectance materials sDA values range between 72.3% of variation 5x9m and 100% of all room variations with depth 5m, 6m and 7m except variations 5x7 and 9x7m.

For southward room with shading and standard materials sDA is fulfilled by all variations with depth 5m, 6m, 7m and 8m except 9x8m. Minimum sDA is 49.7% of variation 5x9m and maximum is 97.7% of variation 8x5m. All improved reflectance material cases fulfil sDA requirement with values from 64.2% of variation 5x9m to 100% of all cases with depth 5m and 6m except 9x6m.

Results show that a total of 40% of southward orientation variations with shading fulfil sDA requirement but not mDF. (Figure 5). 52% of variations with standard materials, i.e. variations 6x6m and 8x6m, all those with depth 7m, 8m except 9x8m, and variations 8x9m and 9x9m. 28% of variations with improved reflectance materials, i.e. 6x8m, 8x8m and all those with depth 9m.

None of the south facing room variations fulfil ASE 1000/250 ≤10% requirement, the minimum being 10.4% of variation 5x9m with shading and the maximum 45.4% of variation 8x5m without shading.

The majority of the eastward room variations without shading and with standard materials fulfil the sDA requirement (Figure 6). The variations not fulfilling are 9x7m and all those with depth 8m and 9m except 8x8m and 9x9m. The maximum sDA value is 97.4% of variation 8x5m. All the room variations without shading and with improved reflectance materials fulfil the sDA requirement with a range between 56.5% of variation 5x9m and 100% of all variations with depth 5m except 5x9m and variations 6x6m and 8x6m.

Less than half the east facing variations with shading and standard materials fulfil sDA requirement, i.e. all those with room depth 5m, 6m except 9x6m and variations 6x7m and 8x7m. Except variations 9x8m, 5x9m and 7x9m the majority of the cases with improved reflectance materials fulfil the requirement between the range 56.2% of case 6x9m and 100% of cases 5-8x5m (width x depth).

A number of east facing room variations fulfil mDF but not sDA (Figure 6). Without shading and with standard materials 36% of variations, i.e. 9x7m, all of those with depth 8m except 8x8m and 9m except 9x9m. With shading and standard materials variations 9x6m, 5x7m, 7x7m and 9x7m. With shading and improved reflectance material variations 9x8m, 5x9m and 7x9m. Among all cases three fulfil sDA but not mDF.

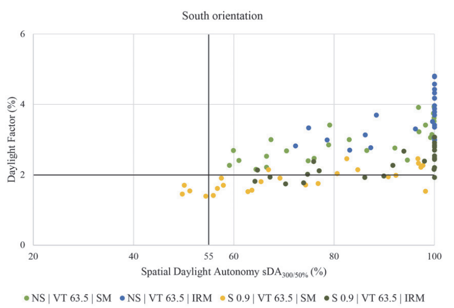

Figure 5: mDF and sDA for south orientation. In the lower-right sector variations fulfilling sDA but not mDF.

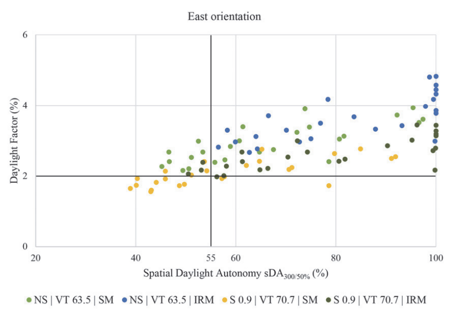

Figure 6: mDF and sDA for east orientation. In the upper-left sector variations fulfilling mDF but not sDA.

Conversely to south facing room variations all of the 50 analysed east facing variations fulfil the ASE 1000/250 ≤10% requirement. All of the calculated ASE values are in the small range between 0% and 1.8% for the variations without shading and between 0% and 0.2% for the variations with shading.

For the north orientation are analysed room variations without shading, with standard and improved reflectance materials, but not variations with shading, for a total of 50. The reason is that rooms facing north at Tallinn latitude and during the occupied hours rarely have direct solar access and do not have overheating problems. This is confirmed by the Annual Sunlight Exposure value 0% for all the 50 variations without shading.

For northward room cases with standard materials sDA is fulfilled by all the variations with depth 5m and 6m except 9x6m (width x depth) and by variations 6x7m and 8x7m (Figure 7). When improved materials are used sDA is fulfilled by all room variations with depth 5m, 6m, 7m, 8m except 5x8m and 9x8m and by the two largest width variations of room depth 9m.

Also for north orientation a number of variations fulfil mDF but not sDA requirement (Figure 7). 56% of variations with standard materials, i.e. variation 9x6m, all variations with room depth 7m except 6x7m and 8x7m, and all variations with room depth 8m and 9m. When finishing materials with improved reflection are used 20% of variations fulfil mDF but not sDA, i.e. variations 5x8m, 9x8m and all variations with room depth 9m except 8x9m and 9x9m.

Daylight performance of westward orientation variations for Spatial Daylight Autonomy 300/50% ≥ 55% are consistent with east facing room cases inasmuch a number of variations fulfil mDF but not sDA requirement, being the westward cases in a larger number comparing those of the opposite façade (Figure 8).

For west facing variations without shading and standard materials sDA is fulfilled by all room cases with depth 5m, 6m except 9x6m (width x depth) and cases with depth 7m except variations 6x7m and 8x7m. When improved reflectance materials are used, in association with no external obstruction provided by shading device, sDA requirement is fulfilled by the majority of room cases.

All room variations with depth 5m, 6m, 7m and 8m except case 5x8m fulfil sDA requirement.

For westward variations with shading and standard materials few cases fulfil sDA requirement, i.e. all room cases with depth 5m except 9x5m, and among cases with depth 6m those with width 6m, 7m and 8m. The majority of variations with shading and with improved reflectance materials fulfil sDA requirement. Those not fulfilling are variation 9x7m and all those with room depth 8m and 9m.

Among all the room orientations, the west facings are those with the highest number of variations which fulfil mean Daylight Factor ≥ 2% requirement but not Spatial Daylight Autonomy 300/50% ≥ 55% (Figure 8). For variations without shading and standard materials 56% fulfil mDF but not sDA and 28% among variations without shading and improved reflectance materials. Also 28% of variations among those with shading and with standard materials fulfil mDF but not sDA and 40% for the cases with shading and improved materials.

Annual Sunlight Exposure for west orientation variations is consistent with eastward ones being the results for all the cases ASE 0%. This way daylight predictions state that no extended in time glare effects are expected on both east and west orientations as well as for north one.

Summary of daylight metrics results comparison

Taking into account all the variations for each of the four different orientations the number of cases for which mDF is fulfilled but sDA is not outnumber the cases for which sDA is fulfilled but mDF is not (Table 7).

Table 7: Variations fulfilling only mDF or sDA.

	mDF ✓ - sDA ✗	sDA ✓ - mDF ✗
South	-	20%
East	16%	3%
North	38%	-
West	38%	-

For south facing room variations 20 cases out of 100 fulfil sDA but not mDF. For eastward room variations 16 and 3 cases out of 100 fulfil mDF but not sDA and sDA but not mDF respectively. For north facing room cases 19 out of 50 and for westward room variations 38 out of 100 fulfil mDF but not sDA. Daylight metrics result differences are discussed further in section Discussion.

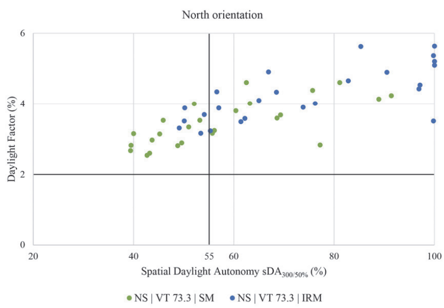

Figure 7: mDF and sDA for north orientation. In the upper-left sector variations fulfilling mDF but not sDA.

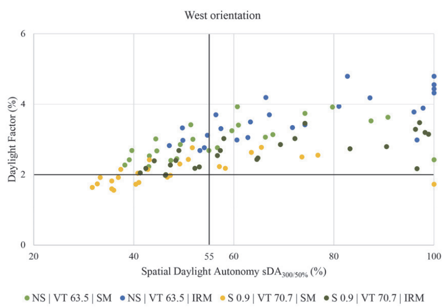

Figure 8: mDF and sDA for west orientation. In the upper-left sector variations fulfilling mDF but not sDA.

Overheating simulation results

Results of overheating simulations are presented and relation with mDF is analysed for room combinations only with standard materials. Alike for sDA, mDF results are presented for different orientations due to different glazing VT and use of shading, and to analyse relation with overheating. Relation with ASE is presented in next section Discussion.

For south orientation without shading all rooms exceed overheating limit and fulfil the mDF requirement (Figure 9). Classrooms with 5m depth are overheated up to 190°C·h and have minimum mDF 2.16%. Adding shading helps to prevent all the rooms from overheating, but larger room depth reduces significantly daylighting. With the use of shading overheating is between 30°C·h and 45°C·h and mDF ranges between 1.42% and 2.46%.

East orientation results are more spread out. Without shading, room variations with depth 5m, 6m and 7m are overheated up to 175°C·h, and all meet the daylight requirement with minimum mDF 2.16% (same of south). If for both east and west orientations shading is added and façade glass g-value increases from 0.35 to 0.42, room variations divide into three sectors (Figure 10). Rooms with 5m depth are overheated up to 120°C·h as horizontal shading can reduce only partially overheating of small depth rooms and present a minimum mDF of 2.5%.

North façade overheating is analysed only without shading as it is not necessary to block direct sunlight in north orientation. All the rooms meet both overheating and daylight requirements (Figure 11). Overheating is between 33°C·h and 51°C·h.m. Meanwhile, mDF decreases steadily from 4.61% to 2.54% as room depth increases. For north façade, higher glass g-value 0.54 is used to allow more natural lighting entering classrooms.

For West façade without shading 5m depth room variations are overheating up to 117 °C·h (Figure 12), and all rooms meet the daylight requirement with mDF values between 2.16% and 3.93% (same of south and east). Adding horizontal shading and optimized g-value of 0.42, similarly to east, overheating is under control with values between 47°C·h and 82°C·h. In these cases, mDF ranges between 1.56% and 2.77%.

Results show that overheating is not a problem for north orientations. Higher g-value (solar factor) and shading may be used to reduce overheating for other orientations. For south façade, overheating is avoided by adding horizontal shading, but extra shading may lead to less daylight for classrooms with larger depth. For both east and west orientations horizontal shading may help to some limits as simulation results are more outspreaded. Figure 10 and 12 show that it is crucial for façade design to take both mDF and °C·h parameters into account.

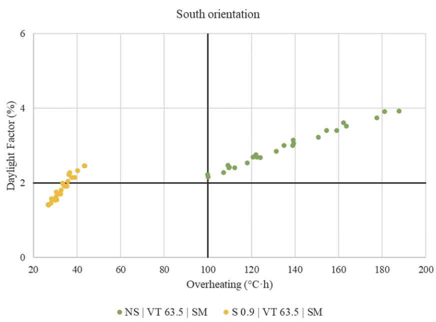

Figure 9: mDF and °C·h plot for south orientation. Upper-right sector variations fulfil mDF but not °C·h.

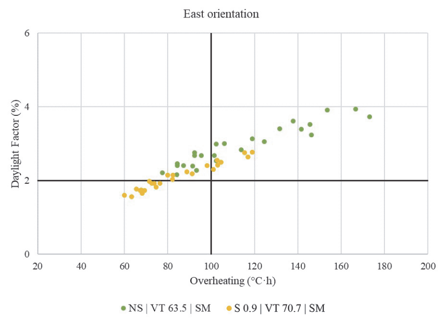

Figure 10: mDF and °C·h plot for east orientation. Upper-right sector variations fulfil mDF but not °C·h

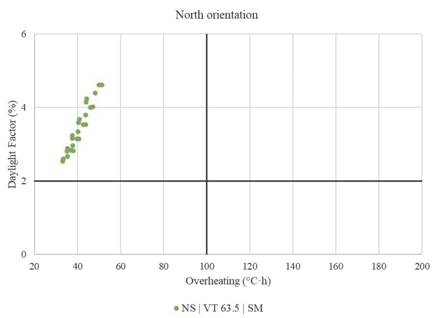

Figure 11: mDF and °C·h plot for north orientation. Upper-left sector variations fulfil both mDF and °C·h.

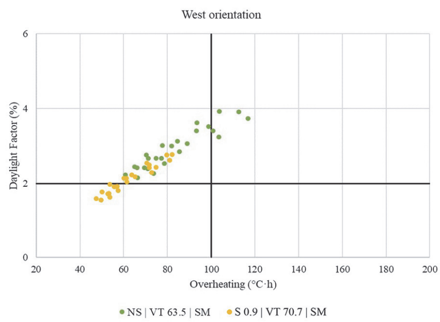

Figure 12: mDF and °C·h plot for west orientation. Upper-left sector variations fulfil both mDF and °C·h.

Discussion

Evidence show the inconsistencies between mean Daylight Factor and Spatial Daylight Autonomy results for a large quantity of room variations for the analysed educational type of building and for the location of Tallinn.

As presented in Table 7 for south facing classrooms 20% of variations fulfil sDA but not mDF. This doesn't constitute an issue and doesn't prevent designing rooms with appropriate quantity of daylight being sDA a more reliable daylight availability metric than DF. Since for all the other room variations the results match, if a classroom fulfils the minimum mDF 2% requirement of the Estonian daylight standard, it automatically fulfils the sDA requirement 300/50% ≥ 55%.

Except for a small quantity (3%) of classroom variations with east orientation which fulfils sDA but not mDF, the majority of the cases presenting inconsistencies of results between the two metrics fulfil mDF but not sDA. These are 16%, 38% and 38% of the room variations respectively with orientation east, north and west. This constitutes an issue. Being Spatial Daylight Autonomy a more reliable metric in predicting daylight availability, using Daylight Factor as required by the Estonian daylight standard do not guarantee the design of classrooms with appropriate quantity of natural light for all building orientations in Tallinn.

These findings show the weakness of Daylight Factor, which is a static and outdated metric, instead than other more recent and advanced metrics which take location climate and building orientation into account. In case of using DF the authors recommend to use different minimum requirements for different orientations. As the results of this study show minimum mDF should be higher than 2% for orientations toward east, north and west for the analysed type of room and location.

The reason of a smaller daylight availability towards east and west than south is due to sun angles with the room window during the occupied hours. During morning (east orientation) from 8am to noon and afternoon (west orientation) from noon to 4pm sun light enters the classroom with a large angle of incidence (angle between the sun and a line perpendicular to the façade) for most of the time. Whereas for south orientation sun light enters the classroom with a small angle of incidence, hence with a larger solar radiation, for a large quantity of occupied hours. Additionally, the larger daylight availability toward east than west (smaller number of variations that fulfil mDF but not sDA), though the operating hours are the same (approx. 4), is due to solar time shift in spring.

The finding of the weakness of Daylight Factor metric in relation to the analysed educational type of building can be assumed also for other types of buildings and interiors with similar operating hours such as office and commercial. For the same reason the finding of this study cannot be extended also to residential dwellings which are considered to be occupied for the entire day. For this building type the appropriateness of Daylight Factor metric in Estonia need to be verified.

Conclusion

The main aim of the present study is to analyse the validity of the minimum value of mean Daylight Factor for educational building classrooms as required by the Estonian standard "Daylight in dwellings and offices". Daylight availability for a classroom model located in the city of Tallinn using the minimum requirement of mDF ≥ 2% is tested against results of more reliable climate-based daylight simulations performed using the approved method Spatial Daylight Autonomy 300/50% ≥ 55%.

Additionally, potential glare and overheating risk, both due to excessive direct solar access, are assessed. The first through the metric Annual Sunlight Exposure 1000/250 ≤ 10% and the latter in relation to Estonian energy efficiency requirements.

The case study of a classroom limits the analysis to one building type, nevertheless assumptions can be extended to other type of buildings. A large number of room variations are analysed, different for size, proportions, orientation, use of shading and material characteristics.

Results show that Daylight Factor analysis in a large number of cases for south orientation variations underestimate and for a larger number of cases toward east, north and west overestimates daylight potentialities for the analysed type of room and location. Findings can be extended to similar building types such as office and commercial which are occupied during the central hours of the 24h day.

On the basis of the findings it is recommended to use more reliable climate-based simulations and metrics to assess more accurately daylight availability in building interiors. A revision of the actual Estonian daylight standard is also recommended and the use of different minimum requirements for different orientations suggested with values of minimum mDF larger than 2% for east, north and west orientations.

The use of improved reflectance materials, in opposition to standard materials as recommended by regulations and simulation good norms, improving daylight availability in building interiors, reduces the number of simulated cases that fulfil one requirement but not the other hence increases the reliability of Daylight Factor metric. Additionally, improved reflectance materials used in this study have properties closer to actual common interior finishing than the recommended standard materials.

According to climate based dynamic simulation results maximum depth for properly daylight classrooms varies depending on orientation, use of shading and material characteristics. Considering the 80% of floor area used in the study, for classroom facing south without shading all the room depths with standard and improved reflectance materials permit properly daylit classrooms. Using shading and standard materials up to 8m depth classrooms and all those with improved reflectance materials are properly daylit. Classrooms facing east without shading and standard materials are properly daylight up to 7m depth, and all of those without shading and improved reflectance materials. With shading and standard materials room depth required for daylit classrooms facing east is maximum 6m which increases to 8m using improved reflectance materials. Classrooms facing north without shading are properly daylit up to 6m depth in case standard materials are used and 8m in case improved reflectance materials are used. West orientation classrooms without shading with depth up to 6m are properly daylit in case of standard materials and up to 8m in case of improved reflectance materials. In case shading is used toward west, well daylit classrooms are obtained only with room depth 5m with standard materials and up to room depth 7m for improved reflectance materials. The difference of depth for properly daylit classrooms toward east and west is due to solar time shift in spring.

Results show as well that potential glare needs to be taken into account in the design of envelope and glazing areas of south facing classrooms. For the other orientations glare probability is small for this type of building and it can be controlled simply by a wise interior desk layout.

Overheating simulation results indicate that room dimensions work the opposite way for mDF and °C·h. Results show clearly that designing classrooms without room conditioning units or cooled supply air requires careful combined analyses of both mDF and °C·h requirements in order to find quite limited and not obvious solutions satisfying both criteria.

Future development of the presented research is to investigate reliability of Daylight Factor requirement of the Estonian regulation through climate-based daylight analysis and overheating simulations for different existing school buildings. Using real classrooms of specific size, orientations and material properties will expand the dataset allowing more reliable evaluations and will permit to test daylight assumptions against specific building use.

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Curriculum vitae

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VFP19041 "Towards a new generation of user-centred Energy Performance Assessment and Certification; facilitated and empowered by the EPB Center” (1.09.2019−31.08.2022)

LEP18058 "Model technical solutions for Haljala nearly zero energy school building” (2.02.2018−31.12.2020)

VEU17098 "Cost reduction of new Nearly Zero-Energy Wooden buildings in the Northern Climatic Conditions” (1.09.2017−31.08.2020)

VFP17100 "Network for Using BIM to Increase Energy Performance” (3.07.2017−3.01.2020)

VE18065 "High windows draught control with convectors and radiators” (20.12.2018−31.12.2019)

LEP19052 "Borehole cooling and energy performance follow up study of nearly zero energy building OLK Hämeenlinna” (1.03.2019−30.11.2019)

V18032 "Underfloor heating, ceiling and air heating efficiency parameters for EN 15316-2 and CEN/TC 130/WG 13” (1.10.2017−30.06.2019)

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LMIN16098 "Cost efficiency of minimum requirements on energy performance of buildings” (30.08.2016−31.10.2017)

LEP16088 "Design solutions for nearly Zero Energy Buildings” (25.07.2016−31.10.2017)

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Lep15002 "Solutions for additional insulation and improvement of ventilation of typical apartment buildings” (5.01.2015−30.04.2015).

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VFP19041 "Towards a new generation of user-centred Energy Performance Assessment and Certification; facilitated and empowered by the EPB Center" (1.09.2019−31.08.2022)

LEP18058 "Model technical solutions for Haljala nearly zero energy school building" (2.02.2018−31.12.2020)

VEU17098 "Cost reduction of new Nearly Zero-Energy Wooden buildings in the Northern Climatic Conditions" (1.09.2017−31.08.2020)

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VE18065 "High windows draught control with convectors and radiators” (20.12.2018−31.12.2019)

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