DOCTORAL THESIS

New Method for Generating Weather Data for Energy Simulation and Cooling Sizing of Buildings

Seyed Shahabaldin Seyed Salehi

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New Method for Generating Weather Data for Energy Simulation and Cooling Sizing of Buildings

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Declaration:

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

Autor's name

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SEYED SHAHABALDIN SEYED SALEHI

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Contents

List of Publications

The present Ph.D. thesis is based on the following publications that are referred to in the text by Roman numbers.

I Seyed Salehi, S. S., Kalamees, T., Kurnitski, J., and Thalfeldt, M. (2024). New typical meteorological year generation method based on long-term building energy simulations. *Building and Environment*, 256, 111504. https://doi.org/10.1016/j.buildenv.2024.111504

II Seyed Salehi, S. S., Kurnitski, J., and Thalfeldt, M. (2026). Cooling design day generation methods' and risk levels' impact on the design capacities and risk of thermal discomfort in a cold climate. *Journal of Building Engineering*, 119, 115346. https://doi.org/10.1016/j.jobe.2026.115346

III Sepúlveda, A., Seyed Salehi, S. S., De Luca, F., and Thalfeldt, M. (2023). Solar radiation-based method for early design stages to balance daylight and thermal comfort in office buildings. *Frontiers of Architectural Research*, 12(6), 1245–1264. https://doi.org/10.1016/j.foar.2023.07.001

IV Salehi, S. S. S., Kurnitski, J., and Thalfeldt, M. (2022). Comparative study of using periodic daily and long-term weather data for cooling system sizing and impact of thermal mass. *E3S Web of Conferences*, 362, 06002. https://doi.org/10.1051/e3sconf/202236206002

V Seyed Salehi, S. S., Ferrantelli, A., Aljas, H. K., Kurnitski, J., and Thalfeldt, M. (2021). Impact of internal heat gain profiles on the design cooling capacity of landscaped offices. *E3S Web of Conferences*, 246, 07003. https://doi.org/10.1051/e3sconf/202124607003

Author's Contributions to the Publications

The author of the thesis is the principal author in all publications except Publication III. Specific contributions to the articles in this thesis are as follows:

I The author conceptualized and developed the novel simulation-based TMY generation methodology that utilizes building energy use and duration curves as primary selection criteria, replacing traditional statistical climate parameter approaches. The author designed and conducted comprehensive dynamic building energy simulations using IDA ICE software with 31 years of climate data (1990–2020), developed the Mean Squared Error normalized by Annual Energy (MSE_AE) statistical error minimization method, and performed validation analysis across multiple building types. The methodology development, statistical analysis, figure preparation, and manuscript writing were carried out by the author. The study demonstrated superior accuracy with consistent deviation values averaging less than 1% for heating and 4% for cooling, compared to improved EN 15927-4 method with 5% for heating and 7% for cooling. Co-authors provided supervision and manuscript review.

II The author conceptualized and implemented the comprehensive analysis of design day generation methods for cooling system sizing in cold climates. The author developed the methodology for systematic evaluation of ASHRAE Fundamentals and ISO 15927-2 standards across different risk levels, conducted dynamic simulations for cooling capacity determination, and performed thermal comfort assessment using PMV analysis. The study demonstrated that ASHRAE Fundamentals provided consistent and reliable results while ISO 15927-2 exhibited fundamental inconsistencies. The author established evidence-based guidance showing 10% risk levels suitable for cooling room units and 5% for AHU systems. All methodology development, simulations, analysis, figure preparation, and manuscript writing were performed by the author. Co-authors provided supervision and manuscript review.

III The author served as second author and contributed to the development of the solar radiation-based prediction method for early design stage applications balancing daylight and thermal comfort. The author conducted building energy simulations for cooling system sizing validation, performed sensitivity analysis of window configurations and thermal performance parameters, and contributed to the computational efficiency improvements through solar radiation-based approaches. The study established practical guidelines for optimizing window-to-wall ratios and solar control strategies in office buildings. The main author led the conceptualization and methodology development, while the author contributed significantly to the simulation work and manuscript preparation.

IV The author conceptualized and conducted the systematic sensitivity analysis of building design parameters affecting cooling system sizing. The author developed the methodology for evaluating thermal mass impacts, internal heat gain variations, window configurations, and occupancy patterns on cooling loads. The study established a clear hierarchy showing solar gains through windows as highest impact, internal heat gains as medium-high (with empirical occupancy profiles demonstrating up to 35% higher demands), window-to-wall ratio changes resulting in 35% larger cooling systems, and thermal mass providing up to 20% cooling capacity reduction potential. The author performed all simulations, statistical analysis, figure preparation, and manuscript writing. Co-authors provided supervision and manuscript review.

V The author conceptualized and developed the methodology for comprehensive analysis of internal heat gain profiles' impact on cooling system design in landscaped offices. The author created detailed simulation models, conducted parametric studies comparing standard EN 16798-1 assumptions with empirical occupancy profiles, and performed analysis of cooling capacity requirements across different office configurations. The study revealed significant differences in cooling demands based on occupancy patterns and workspace layouts, establishing the importance of realistic internal heat gain profiles in system sizing. The author carried out all simulation work, data analysis, figure preparation, and wrote the majority of the manuscript. Co-authors contributed to conceptualization and manuscript review.

Abbreviations

AHU	Air Handling Unit
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BPS	Building Performance Simulation
CV(RMSE)	Coefficient of Variation of Root Mean Square Error
DF	Daylight Factor
DH	Degree-Hour
ECEARTH	EC-Earth Global Climate Model
F-S	Finkelstein-Schafer (statistical method)
HVAC	Heating, Ventilation and Air Conditioning
IDA ICE	IDA Indoor Climate and Energy (simulation software)
MPIESM	Max Planck Institute Earth System Model
nZEB	Nearly Zero-Energy Building
NorESM	Norwegian Earth System Model
PMV	Predicted Mean Vote
TMY	Typical Meteorological Year
TRY	Test Reference Year
WWR	Window-to-Wall Ratio
ZEB	Zero Energy Building

Terms

Design Day	A constructed daily profile of relevant climate parameters representing conditions corresponding to acceptable risk level of exceeding design indoor environment quality parameters (e.g., hottest day) used for sizing HVAC systems.
Degree-Hour	The cumulative temperature exceedance (°C) over a base temperature per hour.
Thermal Mass	The ability of building materials to absorb, store, and release heat, reducing peak loads.
Overheating	Indoor temperature exceeding acceptable thermal comfort thresholds, quantified by temperature excess.
Typical Meteorological Year	A synthetic weather year constructed from measured data, representing typical conditions.
Test Reference Year	A synthetic weather year constructed from measured data, representing typical conditions.
Risk Level	The exceedance probability used to define extreme weather profiles.
Solar Gain Factor	Fraction of solar energy transmitted through glazing (also known as g-value).
Internal Heat Gains	Heat produced inside a building from occupants, lighting, and equipment.
Thermal Comfort	A condition expressing satisfaction with the thermal environment, assessed via standards or PMV.
Passive Design	Architectural measures (e.g., shading, orientation) that regulate indoor climate without mechanical systems.

Symbols

A	Area, m^2
U	Thermal transmittance, W/(m^2·K)
t	Temperature, °C
t_{cool}	Cooling setpoint temperature, °C
DH	Temperature excess in degree-hours (Kh or °Ch)
g	Solar gain factor of glazing or shading (dimensionless)
WWR	Window-to-wall ratio, –
VT	Visible transmittance (fraction of visible light through glazing)
α_s	Solar azimuth angle, °
γ_s	Solar altitude angle, °
Θ	Visible sky angle, °
Δt	Deadband around the cooling/heating setpoint, K
q_{50}	Envelope air leakage rate at 50 Pa, m^3/h · m^2
z	Building height factor (for urban canyon effects)
LL	Overhang depth, m
B	Side-fins or lateral shade depth, m
C	Room length, m
m	Mass, kg
c_p	Specific heat capacity, J/(kg · K)
Q_{gain}	Internal heat gains, W
Q_{solar}	Solar heat gain through windows, W
E_{cool}	Cooling energy demand, kWh
E_{heat}	Heating energy demand, kWh

Introduction

The building sector is responsible for approximately 28% of global energy-related greenhouse gas emissions, making energy-efficient building design crucial for climate change mitigation [1]. Climate change is fundamentally altering the environmental conditions under which buildings operate, necessitating a reevaluation of traditional design approaches to ensure efficient and resilient structures. Because energy simulation and building energy demand estimation are integral parts of energy-efficient design, high-quality climate input data are essential (Publication I).

Buildings designed for the coming decades face greater susceptibility to global warming, rising average temperatures, and increased frequency of heat waves compared to conditions prevalent in the 1990s and early 2000s [1]. This vulnerability is particularly pronounced in northern European climates where cooling demands are increasing while heating needs decrease. The changing climate landscape creates a pressing need to develop more accurate and forward-looking weather data generation methods specifically tailored for building simulation and design.

Current Challenges in Weather Data Generation

Current weather data generation methods focus mainly on climate parameters and insufficiently on building performance outcomes (Publication I; Publication II). The dimensioning of cooling/heating systems and estimating the annual energy consumption of buildings require reliable meteorological data, yet various research has been conducted to provide meteorological data for indoor climate and energy simulations without adequate consideration of building performance [2]. While extensive effort has been devoted to creating standardized climate datasets, these approaches often prioritize statistical representation of meteorological parameters without directly considering how these parameters interact with building performance metrics.

When no hourly database is available for the site, only a few forms of meteorological data may be offered, such as average days extracted from an existing database or fictional data created by a program employing several pre-established models [2]. However, even when hourly meteorological data is available for many places worldwide, the methods for generating typical meteorological years still present significant limitations.

The influence of different climate parameters on building energy use varies significantly depending on climate characteristics and building typology. Temperature, solar radiation, humidity, and wind patterns affect buildings differently based on their location, orientation, construction materials, and use patterns. These complex interactions are often inadequately captured by traditional weather data generation methods that apply standardized weighting to climate parameters regardless of building-specific considerations, while standards propose a general average value for building performance parameters like occupancy. Related evidence has been reported in earlier work Publication V and in Publication IV.

Despite the numerous methods developed for generating Test Reference Year (TRY) and Typical Meteorological Year (TMY) for energy simulations, there are still identifiable issues regarding these methods' accuracy, region-dependent weighting-factor choices, or time-consuming nature. Even though early methods relied on observed meteorological data, they have been found to be largely inaccurate since the impact of different climate parameters is not the same in energy simulation results. Newer methods, which consider different importance for temperature, solar radiation, humidity, and wind, require climate-specific weighting factors for various climatic parameters, which can lead to varying results across regions and require region-specific calibration.

As building codes continue to push for better thermal insulation and air-tightness, the relative impact of various climate parameters shifts. A well-insulated modern building does not perform the same as an old building considering the cooling loads, as the latter may depend more on outdoor temperature. This further highlights the limitations of conventional weather data approaches. Traditional TMY generation methods based on solely statistical or measured climate parameters may not accurately represent the complex interactions between weather conditions and building energy performance.

Design Day Generation Challenges

Current cooling system sizing relies on design methods that may not adequately account for changing climate conditions or may have inefficient generation procedures (Publication II). Design day data provide the expected maximum and minimum temperatures, humidity levels, and solar radiation for a specific location on the warmest and coldest days of the year.

Design practices often use historical data that may fail to capture recent climate trends, potentially resulting in undersized cooling systems that cannot maintain comfortable indoor environments during increasingly frequent heat waves. Conversely, overly conservative approaches may lead to oversized systems with higher capital costs and reduced operational efficiency. Previous studies concluded that conventional design methods overestimate cooling and that ASHRAE-based sizing with historical weather data can produce oversized systems [3, 4].

The main components of cooling system design are input data and the design day generation method. The currently available standard methods used by practitioners are ASHRAE and ISO 15927-2, each with different approaches to risk levels and climate parameter selection. However, these methods have not been systematically compared and evaluated, particularly in the context of cold climates experiencing warming trends. This study addresses this gap by integrating design day analysis with long-term thermal comfort simulations using multi-decade climate data to quantify the impact of risk levels on actual comfort outcomes. Prior evaluation of EN ISO 15927-2 identified key shortcomings, including counterintuitive results such as higher required powers for lower risk levels [5].

Another important factor in design day development is the selected risk level. The impact of risk levels on occupants' thermal comfort is often assumed, while research on this relationship remains limited. This research provides evidence on appropriate risk levels to construct design days that lead to cost-effective cooling sizing without compromising thermal comfort. Considering building-related factors, improvements in envelope energy efficiency have increased the relative importance of internal heat gains and solar radiation in cooling system sizing, particularly in northern climates where this phenomenon is less studied. As buildings become more insulated and airtight, the proportion of cooling load attributed to internal sources such as occupants, equipment, and lighting increases significantly. Similarly, solar gains through windows become more influential in determining peak cooling demands (Publication V).

Research Framework

Objectives and Research Questions

The primary objective of this research is to develop and validate new methods for generating typical meteorological years (TMY) specifically tailored for simulation-based building design. The work also evaluates current design day generation methods and their efficacy, with particular attention to risk levels and climate variables, to support further method development. This research addresses four key questions aimed at improving weather data generation methods for building design and performance simulation.

Research Question 1: Simulation-Based TMY Generation: How can we create more adaptive, easier-to-update TMYs using simulation results as an alternative to methods that rely solely on climate parameters?

Research Question 2: Design Day Method Evaluation/Optimization: Can we validate and optimize existing design day sizing methods, and how effective are different risk level choices?

Research Question 3: Weather Data Impact Assessment: What is the impact of the TMY and cooling design day on simulation outcomes and design choices?

Research Question 4: Building Characteristics and Operational Factors: How do different building characteristics and operational factors affect cooling system sizing requirements?

The investigation aims to establish importance rankings for these factors and provide practical guidance for designers working in cold climates where cooling demands are increasingly important due to climate change.

Method Summary

The research methodology employs dynamic building simulations using IDA ICE software with climate data from Estonia, representing a humid continental climate (Dfb) with no dry season, typical of northern Europe. Answering the research questions requires historical weather data, including hourly temperature, radiation, humidity, wind speed, and wind direction. The case study defines TMY for the Tartu region, Estonia, using weather-station data from 1990 to 2021; fixed periods from this span are used in each article depending on study needs. Four reference buildings representing the Estonian building stock were selected to provide coverage of typical building types in the region. One generic office building representing Estonian office typologies was also developed for theoretical assessment studies.

Three main methodological approaches were developed to address the research questions:

Methodological Approaches

Simulation-Based TMY Generation Method: Statistical error minimization of annual energy use duration curve for representative month selection compared to long-term historical data simulation duration curve (Publication I).

This novel approach shifts the focus from statistical climate parameters to actual building performance metrics when selecting representative months for TMY creation. The method for TMY generation based on simulation results is described without geographical boundaries and can, in principle, be applied in any region to generate a specific TMY. However, for every other region, it is necessary to consider the local construction traditions and choose representative reference buildings.

The simulation-based TMY generation method utilizes cooling/heating needs from long-term simulations of reference buildings, and the corresponding climate parameter for that month is selected instead of direct selection of climate parameters statistically. Several statistical methods were used to identify the most representative months during the process.

Performance Analysis of Design Day Generation methods: Risk-level evaluation according to ISO and ASHRAE methods with thermal comfort assessment

(Publication II).

This systematic approach integrated design day analysis with long-term thermal comfort simulations using multi-decade climate data. Design day profiles are generated according to ISO 15927-2 and ASHRAE Fundamentals.

The analysis involves evaluating temperature data over time to determine the occurrence and severity of overheating in various zones by comparing the simulated hourly room temperatures against predefined thresholds for different risk levels. This assessment analyzed the impact of different risk levels on simulation results for sizing and subsequent thermal comfort.

The framework includes:

- Systematic evaluation of ISO and ASHRAE design day methods
- Thermal comfort validation in cold climate conditions
- Risk-level performance analysis for different cooling system types
- Assessment of the relationship between system sizing and thermal comfort outcomes

Sensitivity Analysis Methodology: Evaluation of the influence of various factors on cooling system sizing requirements. This synthesis draws on prior studies Publication V, together with Publication IVand Publication III.

The research includes comprehensive sensitivity analyses to evaluate the influence of various factors on cooling system sizing requirements, including:

- **Internal heat gain profiles and their temporal variations:** Assessment of how realistic occupancy schedules affect cooling capacity requirements compared to standard schedules
- **Building thermal mass and its impact on peak load shifting:** Analysis of how increased thermal mass delays peak cooling loads but affects total cooling demand
- **Window configurations and solar gain management strategies:** Investigation of how window size and orientation influence cooling needs

Research Contributions and Practical Outcomes

This research makes four key contributions to building performance simulation that have direct practical applications for the building design community:

Novel Simulation-Based TMY Generation Method: A novel approach that uses building energy simulation results instead of climate parameters to determine representative months for TMY generation (Publication I).

The new method used to generate a TMY for Estonia, which is already being used by practitioners, as the result became the official TMY provided by the Estonian Ministry of Climate. As the main finding, it was shown that using building energy simulation results instead of climate parameters to determine the best months for TMY corresponded better with the average annual energy needs.

Key practical advantages:

- **Elimination of climate-parameter weighting-factor selection:** The method eliminates uncertainty in standard methods and the need for region-specific weighting-factor determination in newer methods from the literature, addressing a critical limitation of existing approaches

- **Direct performance correlation:** Direct correlation between weather data selection and building performance outcomes ensures that the generated TMY is optimized for actual building energy use

- **Improved accuracy:** The method has low and consistent deviation values from 31-years results averaging less than 1% for heating and 4% for cooling compared to EN 15927-4 with 5% for heating and 7% for cooling

- **Adaptability:** The developed method has no geographical/climatological limits and can be adapted to different building types and climate zones

- **Easier maintenance:** Easier updating process as new weather data becomes available, enabling frequent adaptation to changing climate conditions

- **Global warming reflection:** The method reflected long-term global warming trends, making it more suitable for future building design

The developed TMY generation method has wide application potential, and it can be recommended to be validated in other climates in the future. In principle, the developed method has no geographical/climatological limits, but it was tested with the Estonian humid continental climate (Dfb) and typical reference buildings.

Comprehensive Design Day Performance Analysis: Systematic evaluation of ISO and ASHRAE design day methods with thermal comfort validation in cold climate conditions (Publication II).

This analysis provides practical guidance that directly addresses current limitations in cooling system design practices as well as limitations of design day generation methods.

Key findings and recommendations:

- **Risk level guidance:** Results indicate that 10% risk levels are suitable for room units, while 5% is preferable for AHU systems.

- **Climate-specific performance:** The analysis revealed that the impact of risk level selection is less pronounced in northern European climates, where solar radiation dominates cooling loads

- **Improvement requirements for ISO 15927-2:** The standard has a complex approach for selecting parameters and produces vague and uncertain results. A clearer and easier path for generating design days is needed.

Building Design Factor Sensitivity Analysis: Importance assessment of internal heat gains, thermal mass, and daylighting impacts on cooling system sizing requirements informed by prior studies Publication V, Publication IV, and Publication III.

These sensitivity analyses offer valuable insights that enable designers to prioritize their efforts and resources on the factors that have the greatest impact on cooling system performance.

Importance ranking and practical implications:

- **Solar gains (high impact):** Solar gains through windows are the most critical factor for cooling system sizing in low- to medium-occupied offices, requiring careful attention to window design and shading strategies

- **Internal heat gains (medium-high impact):** Empirical internal gain profiles, as opposed to standard schedules, significantly affect cooling capacity requirements, highlighting the importance of realistic occupancy modeling

- **Thermal mass (medium impact):** Increased thermal mass delays peak cooling loads but does not substantially reduce total cooling demand, while it has more importance when it comes to annual energy simulations.
- **Window configuration (medium impact):** Window size and orientation have a marked influence on cooling needs, with larger south-facing glazing increasing peak loads and require high quality data input.

The innovation of this thesis lies in developing new TMY method, enabling frequent and easy updating of reference years and providing a sensitivity analysis of input data. This research contributes to more accurate building performance prediction and opens a path towards optimal cooling system sizing in the era of changing climate conditions.

The research follows a systematic progression from identifying limitations in current methods, through developing and validating new approaches, to providing practical guidance for implementation. Each component builds upon previous findings while contributing to the overarching goal of improving simulation data for building design in changing climate conditions.

1 Literature Review

1.1 Climate Change and the Evolution of Building Energy Requirements

Climate change represents one of the most significant challenges facing the building sector in the 21st century. Buildings account for approximately 28% of global energy-related greenhouse gas emissions [6], making improvements in building energy efficiency and optimal use of resources during construction essential to minimize sector's contribution to global warming. The energy performance of buildings is crucial to reduce our impact on global warming, and since energy simulation and estimating a building's energy consumption is a natural part of designing an energy-efficient building, the outdoor climate input data in simulations is essential (Publication I).

The Intergovernmental Panel on Climate Change (IPCC) has documented a clear warming trend globally, with average temperatures rising by approximately 1°C since pre-industrial times. This warming trend is expected to continue, with projections suggesting an additional increase of between 1.5°C and 4.5°C by the end of the century, depending on emissions scenarios and mitigation efforts. Buildings designed for the coming decades face greater susceptibility to global warming, rising average temperatures, and increased frequency of heat waves compared to conditions prevalent in the 1990s and early 2000s [1]. This vulnerability is particularly pronounced in northern European climates where cooling demands are increasing while heating needs decrease, and similar variability has been reported for Finnish future-climate scenarios [7].

The European Union has recognized the critical role of buildings in both climate change mitigation and adaptation through its Energy Performance of Buildings Directive (EPBD) and other policy instruments. The EPBD requires all new buildings to be nearly zero-energy buildings (nZEB) from 2021 onward, necessitating sophisticated design approaches that consider climate conditions. Many countries have already provided regulations while working on road maps to reduce energy usage in the building sector [6]. The major efforts for designing such buildings are passive strategies for reducing cooling and heating demand, implementing systems for utilizing renewable energy sources and using more efficient HVAC (active) systems.

1.2 Typical Meteorological Years: Development, Methods, and Limitations

The concepts of Test Reference Year (TRY) and Typical Meteorological Year (TMY) are both used to address the same climate data representing the climate of a region that can be used for energy simulations (Publication I). Both refer to synthetic weather datasets compiled to represent "typical" conditions for a specific location, usually based on long-term historical observations. The development of reference years for energy simulation modeling started in the 1980s. There were methods of generating meteorological years before that could have a different algorithm to generate typical meteorological years, but all studies and methods were based on actual observed meteorological data [8]. During the 1990s and 2000s, many studies developed TMY or TMY generation methodologies for different regions.

The development of TMY methodologies has evolved significantly since the introduction of the concept in the 1970s. Early approaches focused on selecting the most representative months from historical data based on simple statistical measures of central tendency. Modern methods typically employ the Finkelstein-Schafer (FS) statistics to identify months that best represent the long-term distribution of key climate parameters. Standards such as [9, 10] provide methodologies for generating climate data for building energy simulations and cooling load calculations that rely primarily on historical data, which may not adequately represent the conditions buildings will face during their operational lifetimes. ISO 15927-4 presents a method using Finkelstein-Schafer statistical parameters to generate a TMY from at least 10 years of meteorological data [9]. The method considers temperature, solar radiation, and humidity as the primary determining climate parameters and wind as the secondary parameter for TMY generation. The provided method has been assessed for building simulations and photovoltaic-system design [11, 12].

The risk of using outdated TMYs and peak day sizing data is substantial. Buildings designed using typical historical climate data may experience significant performance gaps as climate conditions change. This risk is particularly pronounced for cooling systems in northern European regions, where historically cooling demands have been modest but are projected to increase significantly due to climate change. Earlier work has shown that conventional air-conditioner sizing can overestimate cooling and that ASHRAE-based sizing with historical weather data can lead to oversized systems [3, 4]. These findings highlight the need for more adaptive approaches to weather data generation that can account for changing climate conditions and their impact on building performance. The TMY for Estonia that practitioners used until 2024 was based on historical data from 1970 to 2000 and developed using traditional methods. This temporal gap necessitates updating to reflect recent climate trends and global warming effects.

Many efforts have been made in the literature to improve TMY development. Regional variations in the effect of climate parameters have led to weighted-parameter approaches. One such study suggested that air humidity and wind speed do not play a significant role in TMY generation for Finland's cold climate and proposed monthly weighting factors for temperature and radiation [13]. However, the weighting factors proposed for the Finnish cold climate differ from those presented for the Italian context, highlighting the regional variability and potential subjectivity of weighting-factor determination [14].

Advanced approaches have emerged to address the limitations of traditional methods. Machine-learning techniques have been used to determine weighting factors and compare training approaches for improving energy-performance estimation [15]. Machine-learning and deep-learning methods have also been used to develop TMYs from meteorological data for the Chinese climate [16]. Alternative perspectives have likewise argued that a single "typical" meteorological year may be insufficient for building performance simulation and that several weather files may be needed instead [17, 18].

Other approaches include extreme reference years for addressing typicality concerns, calibrated TMY generation using quantile mapping for zero-energy buildings, improved TMY generation for the Chinese climate, and evaluation of typical illuminance year generation from long-term data [19, 3, 20, 21]. Various studies have therefore validated TMY-generation methods across different climate zones and applications.

Despite the numerous methods developed for generating TRY and TMY for energy simulations, there are still identifiable issues regarding these methods' accuracy, region-dependent weighting-factor choices, or time-consuming nature. Even though early methods relied on observed meteorological data, they have been found to be largely inaccurate since the impact of different climate parameters is not the same in energy simulation results. Key limitations include: (1) Region-dependent weighting factors - newer methods, which consider different importance for temperature, solar radiation, humidity, and wind, require climate-specific weighting factors for various climatic parameters, which can lead to varying results across regions; (2) Time-consuming nature - the generation of TRY and TMY can be time-consuming and labor-intensive using a number of contemporary methods; (3) Statistical versus performance focus - current methods prioritize statistical representation of climate parameters rather than direct consideration of building performance outcomes; and (4) Maintenance challenges - most TMY methods are difficult to maintain and update, making them less responsive to changing climate conditions.

Some researchers have begun exploring simulation-based approaches. Energy-simulation results have been used for TMY generation, but still within a framework that calibrates the generated TMY against climate-parameter-based methods by minimizing a target deviation [22]. Other studies have compared simulation results based on a typical weather year and an actual weather year in order to derive reliability factors for both system sizing and energy-use estimation [23, 24]. A significant gap remains in developing methods that directly link weather-data selection to building energy use, eliminate the uncertainty associated with weighting-factor determination, and provide more building-performance-oriented weather data.

1.3 Design Day Weather Data and System Sizing Methodologies

The development of design day data for dimensioning cooling and heating systems started in the 20th century [25]. This data provides the expected maximum and minimum temperatures, humidity levels, and solar radiation for a specific location on the warmest and coldest days of the year. A design day represents critical conditions used in building performance simulations for sizing heating, ventilation, and air conditioning (HVAC) systems. It is created based on statistical weather data to reflect peak heating or cooling loads, ensuring that systems are adequately sized for worst-case scenarios [26].

During the mid-20th century, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) initially established design conditions for different locations in the United States [27]. Since then, ASHRAE, the International energy conservation code (IECC), and the European Committee for Standardization (CEN) have published guidelines and standards for calculating design day data for various regions in the world.

Two primary standard methodologies dominate current practice. The ASHRAE Fundamentals handbook offers a comprehensive approach, considering multiple climate parameters and their coincident values. The method includes provisions for different risk levels (0.4%, 2%, 5%, and 10%), allowing designers to select appropriate safety margins based on building type and use. Additionally, ASHRAE provides guidance for adjusting design conditions based on climate trends, acknowledging the limitations of purely historical data. Design day according to ASHRAE consists of hourly data for a single day, including main parameters (dry-bulb and wet-bulb temperature) and additional parameters (wind and radiation) [28]. The method does not involve wind in the primary selection procedure, focusing on temperature and solar radiation as the primary determinants.

ISO 15927-2 provides a procedure for selecting design days based on risk percentiles (1%, 2%, and 5%) [10]. According to the standard, design-day data are hourly data for a single day. Temperature and radiation are mandatory parameters, but additional parameters may be included if needed; leaving that choice to practitioners may lead to subjective and inconsistent design days [5].

Research on design-day-method performance has revealed significant limitations in current approaches. One evaluation of EN ISO 15927-2 across 108 locations in Italy identified key shortcomings, including counterintuitive results such as higher required powers for lower risk levels and a negligible impact of wind speed on the selection process [5]. That study also showed that when different sets of climatic parameters were considered for design-day generation, the selected design days varied substantially, with less than 20% overlap across parameter sets. This means that the design-day selection process depends on practitioner discretion in choosing the parameter set, and different choices can lead to different outcomes. At the same time, over 90% of the selected design days remained consistent when wind was the only varying parameter, which aligns with ASHRAE because that method does not involve wind in the primary selection procedure [28].

Alternative and advanced approaches have emerged to address these limitations. These include clustering-based coincident design-day selection, comparison of radiant and conventional time-series methods for radiant cooling systems, and broader reviews of data-driven and machine-learning-based approaches for occupant-behavior modeling and load prediction [29, 30, 31]. Together, these approaches represent a shift toward methods that can capture more complex relationships between variables.

Performance-assessment studies have consistently identified oversizing issues in current practice. Conventional air-conditioner sizing has been reported to overestimate cooling, and ASHRAE-based sizing with historical weather data has likewise been shown to produce oversized systems [32, 4]. Other work has proposed rational selection methods for risk-based air-conditioning design [33]. A California report found that 40% of rooftop systems were 25% oversized under peak-day-load design methods [34]. Additional studies have explored future scenarios, validated design-day calculation methods, or proposed alternatives to conventional approaches; for example, future-climate variability in dimensioning outcomes has been demonstrated for the Finnish climate, which resembles Estonia [7].

Thermal comfort assessment methods provide essential validation tools for cooling system design. The TAIL method specifies acceptable temperature ranges and exceedance limits, focusing on the percentage of time temperatures can deviate from optimal thresholds [35]. TAIL uses indoor air temperature to assess thermal comfort. The air-temperature criteria of this method for the best building category ranged between 23.5°C and 25.5°C. According to the method, temperatures may surpass the specified range by up to one category for a maximum of 5% of the occupancy time and by up to two categories for no more than 1% of the time when measurements were taken. EN 16798-1 offers a broader approach by classifying indoor environments and standardizing thermal-comfort criteria [36]. EN 16798-1 uses operative temperature for thermal-comfort classification, whereas TAIL uses air temperature because the difference between air and operative temperature is low in low-energy buildings. Traditionally, thermal comfort in buildings has also been assessed with models such as Predicted Mean Vote (PMV) [37]. These models are designed to predict the average thermal sensation of occupants and thereby support HVAC design.

There are significant gaps in the literature regarding risk-based sizing approaches, particularly in cold climate regions. Despite the growing importance of thermal comfort assessment, there remains a lack of robust methodologies for evaluating comfort under extreme climatic conditions in a longer historical period. Conflicting evidence exists regarding the optimal risk levels for different building types and system configurations. Some studies suggest that conventional risk levels may lead to oversized systems in well-insulated modern buildings, while others indicate potential comfort risks with reduced capacity sizing. This conflicting evidence highlights the need for systematic evaluation of design day methods in the context of specific building types and climate zones.

While design days are generated for different risk levels to account for extreme weather conditions, there is limited research on how these varying risk levels impact the sizing of different cooling system components and, consequently, thermal comfort. A cooling system's main objective is to ensure occupants' thermal comfort. However, it remains unclear how system sizing, determined by different risk levels in design day data, affects thermal comfort during operation.

1.4 Cooling Load Sensitivity and Building Performance Factors

The focus on cooling loads in northern European contexts has become increasingly important due to global warming and the relative lack of research in these regions compared to traditionally warmer climates. As average temperatures rise and heat waves become more frequent, even buildings in historically heating-dominated climates require careful consideration of cooling system design. Building energy simulation involves numerous inputs that influence cooling load predictions. These include climate data, building envelope characteristics, internal heat gains, occupancy patterns, system efficiency, and control strategies. The relative importance of these factors varies depending on building type, location, and design objectives. In order to reduce heat gains for efficient cooling design, some passive solutions can be used, e.g. controlling heat gain from the sun using shadings, applying natural ventilation, passive façade design, etc. [38] Implementing such methods will reduce the total cooling demand of the building while increasing the impact of internal heat gains on cooling system size [39]. There is a long list of influential decisions during the design phase that can affect cooling loads specifically from the passive-design perspective. Among them, the parameters related to windows and the thermal mass of building parts are particularly important, as shown in Publication Vand Publication IV.

Thermal mass can play a role in moderating temperature fluctuations and potentially reducing peak cooling loads. The materials used to construct a building can store heat and release it when a temperature difference exists. Selected sensible-heat-storage materials have been catalogued in earlier work [40]. The most common materials are water, wood, concrete, cast iron, sand, different types of brick, and rock. The maximum energy-storage capacity of a 10-mm-thick building part operating between 18 and 26°C for 24 hours is 18 Wh/m^2 for wood, while the corresponding values for concrete and iron are 48 Wh/m^2 and 79 Wh/m^2, respectively. The energy-storage capacity of building components can reduce the total energy required for heating and cooling, but another important impact is so-called peak shifting, in which storage can meet part of the cooling demand during peak periods and reduce pressure on the active cooling system [41]. Research findings indicate that utilizing thermal mass can reduce cooling-system size by up to 5% Publication V. This peak-shifting capability can reduce pressure on active cooling systems and potentially lead to smaller HVAC-system requirements.

Internal heat gains represent a crucial factor in cooling load calculations, particularly in modern, well-insulated buildings. The internal heat gains in total cooling load are important in cold climates but not always in warm climates. In a warm climate for an old building without external wall insulations, Coskun et al. found that the share of internal heat gains in total cooling load can be as low as around 1% [42], while the share of electricity use for equipment usage can be up to 60% of the total electricity use. However, by reducing the internal heat gains from lighting (using efficient LED lights), equipment and small power consumers, majorly laptops and monitors in office buildings, a 60% reduction in cooling loads can be achieved in certain building systems [39]. This demonstrates the significant role that internal gains play in modern, efficient buildings. However, accurate modeling of occupancy patterns and associated internal gains remains challenging. Traditional schedules used in simulation often fail to capture the variability and stochasticity of actual building use. The impact of occupants' behavior on energy consumption and HVAC design in the buildings gained attention in the late 1950's with a focus on window openings and ventilation systems. This attention turned to occupants' behavior relation with energy consumption in the 80's [43]. A very informative chronological review of major methods for occupants' behavior modeling is done by Tam et al. [43]. Zhao [44] defined occupants as "active" and "passive" in the studied zone and used data mining (nominal Classification method) to classify individual behavior and label them. Richardson et al. [45] employed the two-state nonhomogeneous Markov Chain Monte Carlo (MCMC) technique to identify active and inactive users and predict the timing of the occupants' activities. Mahdavi et al. [46] suggested simplified and stochastic models for predicting the annual plug loads. Stochastic-Weibull distribution is used in the study and it concluded that the stochastic model performed better in predicting plug loads peak and distribution compared to simplified methods. The cooling loads obtained with the profile of EN 16798-1 did not significantly differ from the average of other profiles' results Publication V.

Recent studies have employed machine learning and deep learning techniques for occupancy prediction. Wang Zhe et al. [47] and Wang Ran et al. [48] both used such techniques for occupancy predictions. In a wider review, Ferrantelli et al. [49] gathered major methods used for such modeling techniques and selected several methods that are suitable to be used in Building Performance Simulation (BPS) software; a combination of least squares regression and correlations was chosen as the best model for predicting the annual electricity use of tenants.

Solar gains through windows represent another critical factor in cooling load calculations. The optimal window to wall ratio (WWR) has been suggested to be between 0.30 and 0.45 for all sorts of climates and building orientations [50] while considering just extreme cold climates, it is suggested to be around 0.37 or 0.6 depending on the orientation and glazing type [51]. Shadings are also important. Thalfeldt et al. [52] indicated that external shadings are effective to reduce cooling size demand up to 70% while suggesting a specific complex control method to achieve this. There is however lack of studies considering all elements of cooling load calculations all together to integrate the daylighting in the cooling capacity design in a way that practitioners can compare the impact of different cooling loads on sizing. The integration of daylighting considerations with cooling load calculations presents both opportunities and challenges, while increased natural light can reduce artificial lighting loads, it may also introduce additional solar heat gains if not properly managed.

1.5 Simulation Tool

The procedure of estimating and calculating cooling loads in a zone must contain conductive, convective and radiative heat balance for each surface and a general convective heat balance for the zone. The main calculation method for this procedure is Heat Balance (HB) method. This method solves the problem directly through an iterative procedure in which most often a computer must be involved [26]. However, while ASHRAE suggests Heat Balance as the most accurate method, there are several other methods for cooling load calculation described in the handbook. The Radiant

Time Series (RTS) method is a simplified method based on the Heat Balance method. The benefits of the RTS method are not to be iterative and quantifies the contribution of each construction part to the total load which helps practitioners with judgements over different construction parts and zones. Nevertheless, ASHRAE mentions that the RTS method can be used for peak load design and should not be used for annual energy simulations due to its limiting assumptions. Some other methods are also accepted by ASHRAE to be used such as transfer function method (TFM), cooling load temperature difference/cooling load factor (CLTD/CLF) method, total equivalent temperature difference/time averaging (TETDA/TA) method, but since RTS can be effectively replaced with all other methods, they are rarely used [28].

Dynamic building simulation software such as IDA Indoor Climate and Energy (IDA ICE) provides powerful tools for analyzing building performance under various climate conditions and design scenarios [53]. IDA ICE uses the Heat Balance method for cooling load calculations, solving heat transfer equations iteratively to account for conductive, convective, and radiative processes simultaneously. IDA ICE 4.8 and IDA ICE 5 software have been extensively used in researches connected to this thesis. The software provides comprehensive capabilities for modeling building thermal behavior, HVAC systems, and occupancy patterns, making it suitable for detailed performance analysis under various weather conditions.

2 Methodology

2.1 Overall Research Workflow

This chapter presents the methodological framework developed to address the research questions outlined in Chapter 1. The framework comprises two main methodological streams, simulation-based TMY generation and design day performance analysis supported by sensitivity analyses that evaluate how input data and building characteristics influence cooling system sizing requirements.

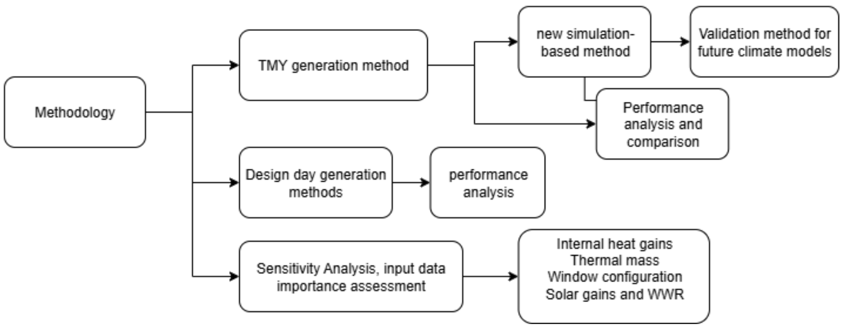

Figure 1: The overall research parts of the thesis showing the integration of different methodological approaches

The methodology of all articles required historical weather data collection, including hourly temperature, radiation, humidity, wind speed, and direction. The research employs dynamic building simulations using IDA ICE software with climate data between 1990 and 2021 from Estonia, representing a humid continental climate (Dfb) with no dry season, typical of northern Europe. Four reference buildings representing building stock in Estonia were chosen as typical building types in the region, as part of the TMY development method.

2.2 TMY Generation Method

To evaluate the novel TMY generation method developed in Article I, as detailed in subsubsection 2.2.1, two additional methods are used for comparison. A brief overview of all methods is provided below:

1. **EN ISO 15927-4 method:**
   - Applies the standard method without climate parameter weighting factors [9]
   - Utilizes climate parameters (temperature, radiation, humidity, wind) on an hourly basis
2. **EN ISO 15927-4 method with weighting factors:**
   - Utilizes the standard method with added climate parameter weighting factors proposed in earlier work [13]
   - Utilizes climate parameters (temperature, radiation, humidity, wind) on an hourly basis
3. **Proposed simulation-based TMY generation method:**

- Utilizes cooling/heating needs from long-term simulations of reference buildings instead of climate parameters
- Cooling/heating needs are derived from hourly long-term simulation results

A summary of the processes needed for generating TMY based on these three methods is shown in Figure 2.

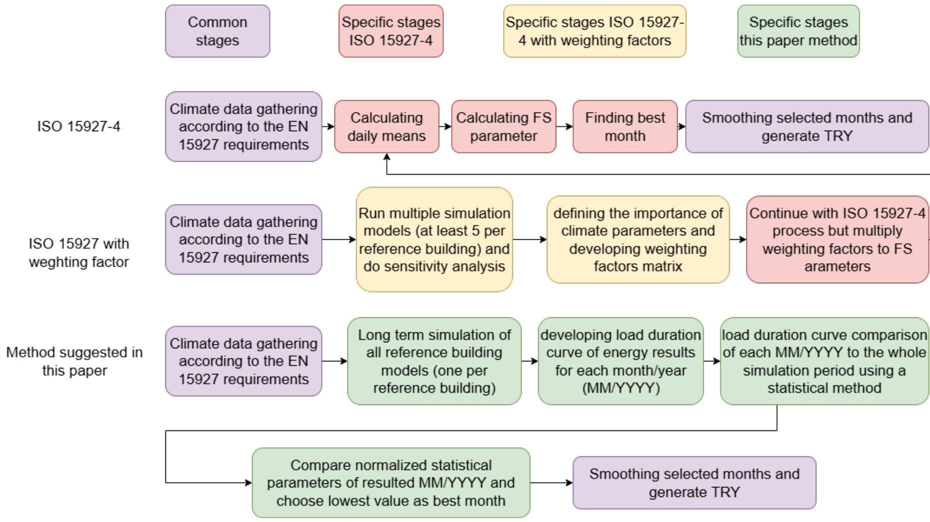

Figure 2: Summary of processes needed for generating TMY based on ISO 15927-4, the adjusted ISO 15927-4 approach proposed by Kalamees et al. ([13]), and the method suggested in this thesis.

The methodology of all approaches requires historical weather data collection, including hourly temperature, radiation, humidity, wind speed, and direction. The case study is conducted to define TMY for the Tartu region, Estonia, using historical weather data obtained from a weather station in the Tartu region from 1990 to 2020. For the proposed method (Method 3), four reference buildings representing the building stock in Estonia were chosen as described in subsection 2.4. For Method 2, weighting factors specific to the Estonian region are applied as presented in earlier work [13].

It is important to note that the current TMY for Estonia that practitioners use is based on historical data from 1970 to 2000 and was developed using Method 1. This baseline is also included in the result presentations to reflect the global warming effect and demonstrate the necessity for updating the Estonian TMY.

2.2.1 Simulation-Based TMY Generation Approach

This study presents a new method of TMY generation and the results compared with the most typical methods from the literature in the Estonian context. The goal was to reduce the uncertainty and calibration effort associated with choosing weighting factors for TMY generation and to increase the speed and accuracy of energy simulation estimations. This study's novelty lies in choosing the best representative months for the TMY based only on the long-term energy simulation results of the reference buildings. This means that the historical hourly data of temperature, radiation, humidity, or other climate parameters were used to model and simulate the hourly cooling/heating need, which was then used to select the most representative month.

To evaluate the proposed method, two other methods are used for comparison as mentioned earlier: the EN ISO 15927-4 standard method and the EN ISO 15927-4 method with weighting factors provided in earlier work [13].

2.2.2 Climate Parameter-Based Method Implementation

The method presented in earlier work [13] is an adjusted version of ISO 15927-4 [9]. Consequently, both methods are discussed concurrently in this section. The adjustment involves assigning varying significance to different climate parameters each month. For instance, outdoor temperature plays a more crucial role in determining energy usage during winter months in northern Europe; therefore, it has a higher significance.

The following procedure was derived from EN ISO 15927-4, which should be followed for every climate parameter p (temperature, solar radiation, and humidity):

a) Calculate the daily means of each climate parameter, p

b) For each calendar month (MM/all years), calculate the Cumulative Distribution Function (CDF) of the daily means over all years. For CDF calculation, the daily mean values should be sorted in increasing order and ranked, and the rank is divided by the total number of values.

$$\phi(p,m,i) = K(i)/(N+1) \tag{1}$$

Where K(i) is the rank order of the ith value of the daily means within that calendar month (m) in the whole dataset, and N is the total number of data points for that month in the whole dataset.

c) Sort all the values for that month and that year in ascending order, and then use Equation 2 to get the cumulative distribution function, F(p,y,m,i), of the daily means within each calendar month for each year of the data set:

$$F(p,y,m,i) = J(i)/(N+1) \tag{2}$$

Where J(i) is the rank order of the ith value of the daily means within that month (m) and that year (y).

d) For each calendar month and each year, add the Finkelstein-Schafer (F.S.) value of the climate parameters using Equation 3 according to ISO 15927-4 [9] and Equation 4 according to [13], and rank the result.

$$F.S(y,m)total = \sum_{n,p=1} F.S(p,y,m) \tag{3}$$

$$F.S(y,m)total = \sum_{p=1}^{n} \big(w(p,m) \times F.S(p,y,m)\big) \tag{4}$$

where $w(p,m)$ is the weighting factor for parameter p in month m as given in Table 1. After calculating the total F.S. value for all candidate months, the three months with the lowest total F.S. are retained as the top-ranked candidates. The final representative month is then selected as the candidate whose monthly mean wind speed deviates least from the multi-year mean wind speed for that calendar month.

In accordance with earlier work [13], humidity is omitted from the weighted formulation and radiation receives zero weight in November–February, when dry-bulb temperature is treated as the dominant parameter for month selection.

Table 1: Weighting factors for climate parameters suggested in earlier work [13].

Month	W_t (Dry-bulb Temp)	W_h (Humidity)	W_r (Radiation)
Jan	1.0	0.0	0.0
Feb	1.0	0.0	0.0
Mar	0.8	0.0	0.2
Apr	0.8	0.0	0.2
May	0.5	0.0	0.5
Jun	0.5	0.0	0.5
Jul	0.5	0.0	0.5
Aug	0.5	0.0	0.5
Sep	0.8	0.0	0.2
Oct	0.8	0.0	0.2
Nov	1.0	0.0	0.0
Dec	1.0	0.0	0.0

2.2.3 Simulation-Based Method Implementation

This new method aims to create a Typical Meteorological Year which, after being used in simulations, results in hourly cooling/heating needs with the closest possible load distribution function curve to the cooling/heating needs resulting from long-term simulations using meteorological data (Publication I). The proposed method uses long-term simulation results for the assessment instead of actual climate parameters.

The workflow of the long-term hourly simulation-based method is summarized in the following points:

1. Gather hourly heating and cooling needs from a 31-year simulation using IDA ICE 4.8 software for each reference building [53] (4 reference buildings are used for Estonian context)

2. Create load duration curves from hourly heating and cooling needs for each month and each year

3. Compare each month's load duration curve to the load duration curve of that month during the whole 31 years using statistical methods

4. Select the month with the lowest deviation for each calendar month (method choice for calculating deviation is further analysed)

5. Smoothing, according to EN 15927-4, should be implemented before combining months and creating the final TMY

To find each month of the TMY, the load duration curve of each month was compared to the load duration curve of that month during the whole 31 years. (For example, the curve of January 1990 compared to the curve of all January months combined from 1990 to 2020). The energy needs of space and ventilation heating and cooling were included, and the heating and cooling needs had positive and negative values, respectively.

Several statistical methods for measuring deviation were employed to implement such a comparison, as listed in Table 3.1. Different methods were chosen to measure each method's accuracy and find the method with the least deviation in energy simulation results.

Table 2: Statistical methods employed to generate TMYs in this study.

Method	**Formula**
Mean Absolute Error, Normalized by annual energy (MAE_AE)	MAE$(y,\hat{y}) = \frac{1}{n}\sum \mid y_i - \hat{y}_i \mid / TE(b_j)$
Mean Absolute Error, Normalized by dataset range (MAE_DR)	MAE$(y,\hat{y}) = \frac{1}{n}\sum \mid y_i - \hat{y}_i \mid / (\max(y_i) - \min(y_i))$
Mean Squared Error, Normalized by annual energy (MSE_AE)	MSE$(y,\hat{y}) = \frac{1}{n}\sum (y_i - \hat{y}_i)^2 / TE(b_j)$
Mean Squared Error, Normalized by dataset range (MSE_DR)	MSE$(y,\hat{y}) = \frac{1}{n}\sum \left(\frac{y_i - \hat{y}_i}{\max(y_i)-\min(y_i)}\right)^2$
Root Mean Squared Error, Normalized by dataset range (RMSE_DR)	RMSE$(y,\hat{y}) = \sqrt{\frac{1}{n}\sum \left(\frac{y_i - \hat{y}_i}{\max(y_i)-\min(y_i)}\right)^2}$

Where y_i and $\hat{y}_i$ are the heating/cooling needs of each data point for a month and the corresponding 31-year load duration curve data point, respectively; n is the total number of available data points; and TE(b_j) is the total annual energy use of each building type.

The reference buildings used for the case study of Estonia is presented in the subsection 2.4 section.

2.2.4 TMY Comparison and Validation basis

For the illustration of different TMY data resulting from all methods, cooling degree hours and heating degree days are calculated for the hourly temperatures of TMYs as elaborated by Estonian Regulation No 63 [54], and the comparison is presented in the results section. The TMY data was then used to simulate case study buildings, and the annual energy needs were compared.

2.2.5 Cooling Degree Hours

According to Estonian regulation, the risk of overheating shall be calculated for a "critical room" [54]. Since ideal coolers are used to suggest the best TMY, the method used the dry-bulb temperature of the TMYs to calculate the number of hours with the high demand for cooling during summer.

The formula for calculating degree hours is as follows:

$$DHtb = \sum (ti - tb)_+ \tag{5}$$

where DHtb is the temperature excess in degree-hours compared to the base temperature tb (°C), ti is the hourly mean outdoor, and j is the total number of hours with a temperature higher than the base temperature during the given period. The cooling degree hours are assumed to be from the 1st of April to the 30th of September.

2.2.6 Heating Degree Days

Heating degree day compares a location's mean outdoor temperature to a base temperature. The formula for calculating degree days is as follows:

$$HDDd = -\sum (ti - tb)_- \tag{6}$$

where HDDd (°C) is the temperature difference, tb (°C) is the base temperature, ti (°C) is the daily mean outdoor temperature, and j is the total number of days with a mean temperature lower than the base temperature during the given period. Typically, the degree-days base temperature of 13°C is used for old and well-insulated residential buildings and 17°C for office buildings (Publication I).

2.3 Design Day Generation and Risk-Level Sizing

2.3.1 Design Day Generation Analysis

The analysis methodology comprises the generation of design days using established standards, the sizing of cooling system components through dynamic simulations, and the evaluation of the performance of these systems during a long period with heat waves that occurred between 1990 and 2022 in Tartu, Estonia, a humid continental climate (Dfb) with cold winters and mild to warm summers (Publication II).

By comparing several techniques for calculating design days and assessing their influence on system size and thermal comfort, the study intends to propose optimal strategies for designing cooling systems.

2.3.2 Research Process Overview

The activities listed below are a brief description of the process of this analysis:

1. Generating design days with different risk levels defined in relevant standards ([28] and [10])

2. Developing 4 cases of a generic open-plan office floor (provided in subsubsection 2.4.4 and sizing the cooling plant, AHU cooling coil, and room units of a reference building using dynamic simulations based on the identified design days for all risk levels

3. Conducting long-term simulations with historical weather data of years between 1990 and 2022 to analyze room temperatures using the cooling system components' sizes derived in the previous step

4. Assessing the impact of risk levels on thermal comfort during historical heat waves by assessing maximum room temperatures and quantifying the number of occupied hours with a temperature higher than the maximum allowed in every classification defined by standard (TAIL and EN 16798-1 [35, 36])

5. Discussion and recommendations for the best practices in sizing different cooling system components

2.3.3 Design Day Generation Methods

Two design day generation methods were compared:

ASHRAE Fundamentals Method

Design day according to ASHRAE consists of hourly data for a single day, including main parameters (dry-bulb and wet-bulb temperature) and additional parameters (wind and radiation). The process follows these steps:

1. Gathering weather data for Tartu, Estonia, from 1990 to 2022

2. Identifying dry-bulb and wet-bulb temperatures representing three frequencies of occurrence (0.4%, 2%, 5% and 10% named as risk levels)

3. Identifying wind speed corresponding to the dry-bulb temperature with a 5% frequency of occurrence

4. Theoretical calculation of the radiation for the specific location, based on its latitude, longitude and height with a clear sky

ISO 15927-2 Method

According to ISO 15927-2 [10], design-day data are also hourly data for a single day. Mandatory parameters are temperature and radiation. Other parameters can be included if needed, but leaving the choice of which parameters to include with the practitioners may lead to design day outcomes that depend on practitioner choices and may therefore be inconsistent.

The process includes:

1. Gathering weather data for Tartu, Estonia, from 1990 to 2022

2. Identifying the parameters needed to generate the design day. Temperature and radiation are mandatory parameters; dew point temperature was chosen in this study as extra parameter to have a more comparable result with ASHRAE

3. Identifying mean daily dry-bulb and dew-bulb temperature and total global irradiation representing three frequencies of occurrence (1%, 2% and 5% named as risk levels)

4. Identification of the design day using an iterative process:

   a. Start with an initial error range (error band) for each parameter, as defined by the standard

   b. For each calendar month and risk level, identify days where the daily average values of all parameters fall within this initial error range

   c. If only one day meets the criteria, that day is selected as the design day

   d. If multiple days meet the criteria, progressively narrow the error range until only one day is left

   e. If no days meet the criteria, gradually widen the error range until a suitable design day is identified

The error ranges for identifying design days in ISO 15927-2 are defined for each parameter and adjusted iteratively during selection. For all temperature-related parameters (e.g., dry-bulb temperature, dew-point temperature), the error range is defined with Equation 7, and for global radiation, Equation 8:

$$\text{Range} = 0.5 \pm X \cdot 0.1 \tag{7}$$

$$\text{Range\_rad} = 50 \pm X \cdot 10 \tag{8}$$

Where X represents the iteration interval, consistent across all parameters, X is incremented by 1 in each step, progressively widening the error band when no suitable day is found within the current range.

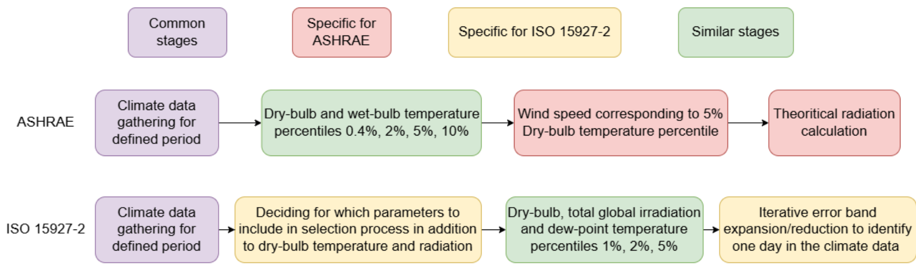

Figure 3: Schematic view of the design day generation methods

2.3.4 Thermal Comfort Requirements and Assessment

In order to assess the effectiveness of the risk levels in design day methods and compare their approach, a simple assessment method is developed considering simple thermal comfort. As discussed in the literature review, buildings with well-insulated envelopes and controlled ventilation tend to show only a narrow difference between air and operative temperature [35]. Therefore, air temperature is used in this study for the thermal comfort assessment.

2.3.5 Temperature Setpoint Justification

To justify the 25°C air temperature setpoint, the following reasoning is relied upon (Publication II):

- Category II is the default standard for new buildings according to EN 16798-1 [36]
- The upper limit of 26°C for operative temperature in Category II can be met with a 25°C air temperature setpoint, assuming a maximum 1°C difference between air and operative temperature
- In this analysis, compliance with Category II is the primary objective, allowing 5% of the time to be in Category III, meaning air temperature should remain below 26°C
- Additionally, 25°C is the temperature setpoint for modeling Estonia's energy use of non-residential buildings [55]

To clarify the approach to thermal discomfort assessment, this list can be provided:

- The total hours during the simulated period when the air temperature exceeded the 25°C threshold
- The number of hours in a continuous 30-day period with temperatures surpassing the 25°C thresholds according to TAIL criterion of 5% accepted excess by 1°C
- The maximum temperature deviations above the threshold during occupied hours

2.3.6 Cooling System Sizing Procedure

The sizing procedure started with modeling ideal coolers with unlimited capacity in all zones together with air handling unit and chiller with very large capacities. Using generated design days for every month based on the two above-mentioned methods, iterative simulation has been done, and maximum capacities for the cooling device, air handling unit cooling coil, and the cooling plant (which is accumulated simultaneous cooling need of both air handling unit and zone devices) derived from models for each building type (Publication II).

The resulting capacities were then re-entered in models and long-term simulations conducted with climate data of Tartu from 1990 to 2022. Simulations logged hourly air temperatures and cooling device outputs to evaluate the system's ability to maintain thermal comfort and meet cooling demands.

2.4 Simulation Design Data

2.4.1 Overview of Building Models and Research Applications

This research employs multiple building simulation models across different methodological components, each selected to address specific research objectives. Table 3 provides a comprehensive overview of which building models and typologies were used for each research purpose, along with the number of cases and variations analyzed.

Table 3: Overview of building models and typologies used across different research components

Research Component	Building Models Used	Total Cases	Purpose and Variations
TMY Generation (Simulation-based method)	▪ Office with small windows ▪ Office with big windows ▪ New single-family house ▪ Old single-family house	4	Reference buildings representing Estonian building stock with varying solar heat gain proportions for heating/cooling needs assessment
Design Day Generation & Risk-Level Sizing	▪ Generic open-plan office floor	4	Single generic office model with variations in window sizes (small/big) and thermal mass (light/heavy) for cooling system component sizing
Cooling System Sizing Sensitivity Analysis	▪ Generic open-plan office floor	16	Generic office with comprehensive variations: ▪ Window sizes: 2 types (small/big) ▪ Thermal mass: 4 types (very light to very heavy) ▪ Internal heat gains: empirical and standard profiles ▪ Occupancy patterns: various schedules

The selection strategy follows a hierarchical approach where:

Reference Buildings (4 models): Used for TMY generation, these models represent the Estonian building stock diversity. The office buildings with different window-to-wall ratios (30% vs 60%) and single-family houses with different insulation levels capture varying solar heat gain proportions in building heat balance, which is crucial for accurate TMY development.

Generic Office Model (1 base model with variations): Used for design day analysis and cooling system sizing studies, this model allows controlled parametric analysis. The focus on a single building type enables detailed investigation of cooling system performance under different design conditions while maintaining consistency across comparative studies.

Parametric Variations: The generic office model incorporates systematic variations in key parameters affecting cooling loads: window sizes (affecting solar gains), thermal mass (affecting peak load timing and magnitude), and internal heat gain profiles (affecting base cooling loads). This approach enables comprehensive sensitivity analysis while maintaining computational efficiency.

The differentiation in model complexity and number of cases reflects the specific requirements of each research component: TMY generation requires representative building stock diversity, while cooling system sizing requires detailed parametric control for sensitivity analysis.

2.4.2 Sensitivity Analysis of Building Design Parameters

This component of the methodology focuses on increasing the understanding of the cooling demand at the zone level (i.e. not focused on the building as a whole). To achieve this goal and understand how different elements affect cooling size, prerequisite research has already been conducted in earlier studies Publication V, [56], together with Publication IVand Publication III. For internal heat gain impact assessment, several weekly internal heat gain profiles were selected from a large set of tenant-based electricity use measured in 4 office buildings in Tallinn. The selection was based on maximum daily or weekly peak loads of an office space per floor area. The suggested occupancy schedule by EN 16798-1, alongside the selected profiles, were used to dimension ideal coolers in the zones of a generic floor model of a landscape office plan and variable window sizes and thermal masses of the building parts. The model characteristics included:

- Variable window sizes (small and big windows)
- Different thermal mass configurations (light and heavy structure)
- Various internal heat gain profiles (empirical and standard)
- Different occupancy patterns and schedules

The purpose of prerequisite studies were to increase the understanding of the cooling demand by considering occupancy, window size, shading, single/open plan office and the existence of construction parts with different thermal masses which can affect the cooling system sizing. The research aims to evaluate different internal heat gains models in order to find the best model for a reliable and optimal zonal cooling system sizing.

While ASHRAE suggests Heat Balance as the most accurate method, there are several other methods for cooling load calculation described in the handbook. The Radiant Time Series (RTS) method is a simplified method based on the Heat Balance method. in this study Heat Balance method is used using IDA ICE software.

The building model that had varied windows size and construction material used for the assessment is Generic building model, which details provided under subsubsection 2.4.4

2.4.3 Reference Building Models

Four building simulation models were selected as reference buildings. An office building model and a single-family detached house were chosen to capture the differences in usage and operation profiles of non-residential and residential buildings. These two models were adjusted to have a reference building stock with varying proportions of solar heat gains in the heat balance of the buildings.

The reference buildings used are as follows:

- Office building with small windows
- Office building with big windows
- Single-family house representing new building with highly insulated envelope

- Single-family house representing old building with poorly insulated envelope

For office buildings, the small window sizes are half the big windows to consider the influence of the solar heat gains on the heat balance. The windows in the old house have doubled thermal transmittance to represent an old house. Figure 4 shows the building models.

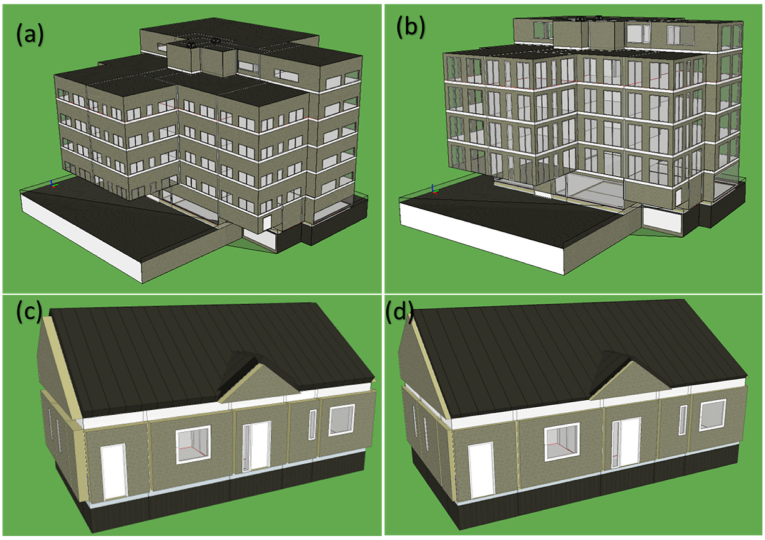

Figure 4: 3D Model of the reference buildings. (a) office building with small windows, (b) office building with big windows, (c) single-family house with thick walls (lower U value, representing new house), and (d) single-family house with thin walls (representing old house).

Building Specifications: Building specifications and simulation parameters are listed in Table 4, Table 5, Table 6 The usage profiles for internal heat gains are according to the EN 16798-1 open-plan office and detached-residential-house profiles [36]. The solar heat gain coefficient of glazed areas was 0.5 for houses and 0.3 for office buildings.

2.4.4 Generic Building Simulation Model

The building body specification and the general plan view of the offices are shown in Figure 5 and Figure 7. The simulation parameters are listed in Table 7, Table 8. The occupancy profiles are shown in Figure 6

The material properties of each layer in the structure are from the IDA ICE material database [53]. Several parameters were determined based on EN 16798-1 [36] or were based on assumptions to facilitate the study. These parameters were as follows:

- The supply air temperature setpoint was 17°C
- The offices and the staircase had a constant air volume flow of 1.4 $l/(m^2 \cdot s)$ during working hours with one hour margin. The flow outside of the working hours is the minimum amount (0.21 $l/(m^2 \cdot s)$) to consider the ventilation of toilets, cleaning equipment room, etc. ventilation working on part load
- The room temperature setpoint was 25°C
- Internal walls were modeled as 30mm light insulation and 52mm gypsum

Table 4: Parameters used in the simulations of the reference buildings.

Parameter	Unit	Office Building	Single-Family House
Gross area	m^2	4958	100
Number of stories	–	6	1
Number of zones	–	42	12
Window-to-wall ratio (WWR)	%	60% / 30%	17%
Occupants	person/m^2	0.0586 (open office profile)	0.532
Equipment load	W/m^2	12.0	2.4
Lighting load	W/m^2	12.0	8.0
Ventilation airflow rate	$L/(s \cdot m^2)$	2.0	0.42
Infiltration (constant rate)	$L/(s \cdot m^2)$	0.056	0.0238
Temperature setpoints (heating/cooling)	°C	21 / 25	21 / 25

Table 5: Building specifications, single-family house.

Structure	Area	Old single-family house		Newly built single-family house	
	(m^2)	U [W/($m^2 \cdot$ K)]	H [W/K]	U [W/($m^2 \cdot$ K)]	H [W/K]
Roof	130	0.2	26.00	0.1	13.00
Slab on ground	100	0.24	24.00	0.12	12.00
External wall	138	0.26	35.88	0.12	16.56
Doors	5.9	2.2	12.98	2.2	12.98
Windows	10.2	1.8	18.41	0.9	9.21
Specific heat loss for heated area H/A [W/($m^2 \cdot$ K)]	–	1.33		0.81	
Total specific heat loss H [W/K]	–	133.30		81.43	

Table 6: Building specifications, office.

Structure	U [W/($m^2 \cdot$ K)]	H [W/K]	**Big windows** [m^2]	**Small windows** [m^2]
Roof	0.16	178.9	1118	1118
External floor above air	0.82	136.9	167	167
Slab on ground	0.82	893.8	1090	1090
Internal slab, b/ garage and 1st floor	0.45	289.8	644	644
External wall	0.3	334.4	1115	1775
External wall basement	–	73.5	245	245
Doors	1.8	27.0	15	15
Windows	0.6	791.4	327	56
Specific heat loss for heated area H/A [W/($m^2 \cdot$ K)]	–	**0.38**	**0.32**	
Total specific thermal transmittance U_A [W/K]	–	**1871**	**1578**	

- The office is located in Tartu, Estonia

The layout includes four offices with dimensions of 16m x 8m and an area of 128 m^2. The offices were 3 m high. The office used in this simulation is located on a middle floor with adiabatic internal floors. The cooling devices in all zones were ideal coolers with coil temperature 15°C.

Table 7: Parameters used in simulations with generic office.

Parameter	**Unit**	**Value**
Gross area	m^2	512 + 88
Occupants	person/m^2	0.09375
Equipment	W/m^2	12
Lighting	W/m^2	6
Ventilation airflow rate	$L/(s \cdot m^2)$	1.4
Infiltration constant air flow rate	$L/(s \cdot m^2)$	0.056
Thermal transmittance (External walls)	$W/(m^2 \cdot K)$	0.2

Table 8: Window specifications used in generic office.

Parameter	**Unit**	**1 (Small)**	**2 (Big)**
Width	m	1.8	2.1
Height	m	1.0	1.9
Area	m^2	1.8	3.99
Window-to-wall ratio	–	0.25	0.58
Total windows per office	–	7	7
Number of panes	–	3	3
Solar heat gain coefficient	–	0.49	0.32
Solar transmittance	–	0.41	0.28
Visible transmittance	–	0.71	0.59
Glazing thermal transmittance	$W/(m^2 \cdot K)$	0.6	0.6

The offices and the staircase had balanced mechanical ventilation with a specific air flow rate of 1.4 $l/(m^2{\cdot}s)$ during working hours, with 1 h margin. The flow outside of the working hours is the minimum amount (0.21 $l/(m^2{\cdot}s)$) to consider the ventilation of toilets, cleaning equipment room, etc. No natural ventilation is modeled other than infiltration mentioned in Table 7. The heat exchange between rooms happens only through internal walls, modeled as 30 mm light insulation and 52 mm gypsum with a U-value equal to 0.62 $W/(m^2{\cdot}K)$.

Four types of structural profiles comprised of walls, floors, and ceilings with different thermal mass characteristics were developed for the comparative analysis:

- **Structure A (Very Light):** Minimum thermal mass configuration
- **Structure B (Light):** Low thermal mass with standard insulation
- **Structure C (Heavy):** High thermal mass with concrete elements
- **Structure D (Very Heavy):** Maximum thermal mass configuration

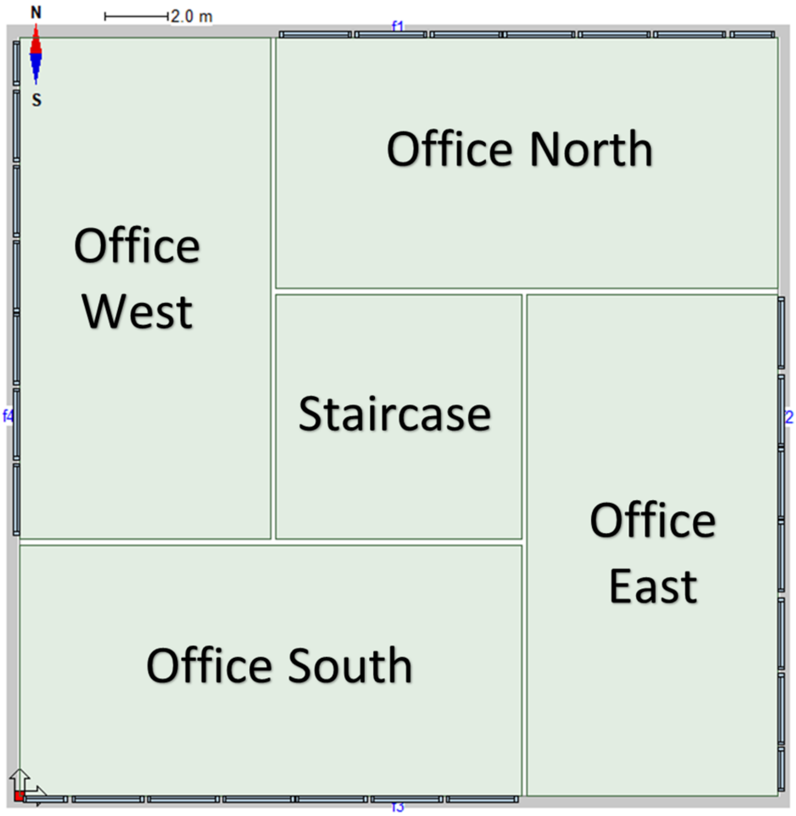

Figure 5: General office plan and 3D view of the models with different Window-to-Wall Ratios and shading. CLT in wall composition is an acronym of Cross-Laminated Timber.

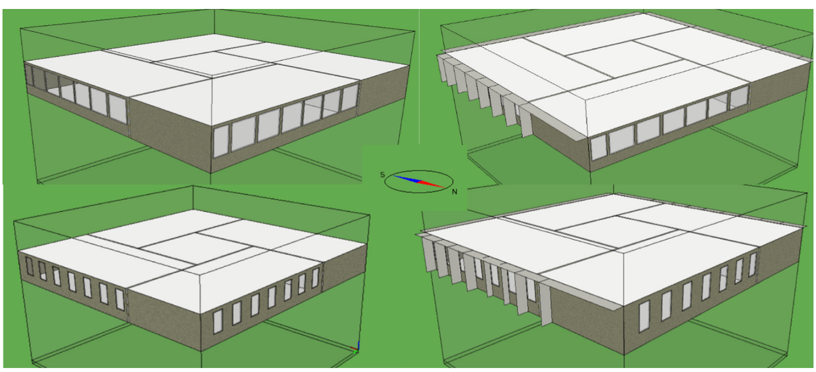

Figure 6: The occupancy and fan operating schedules used in this study.

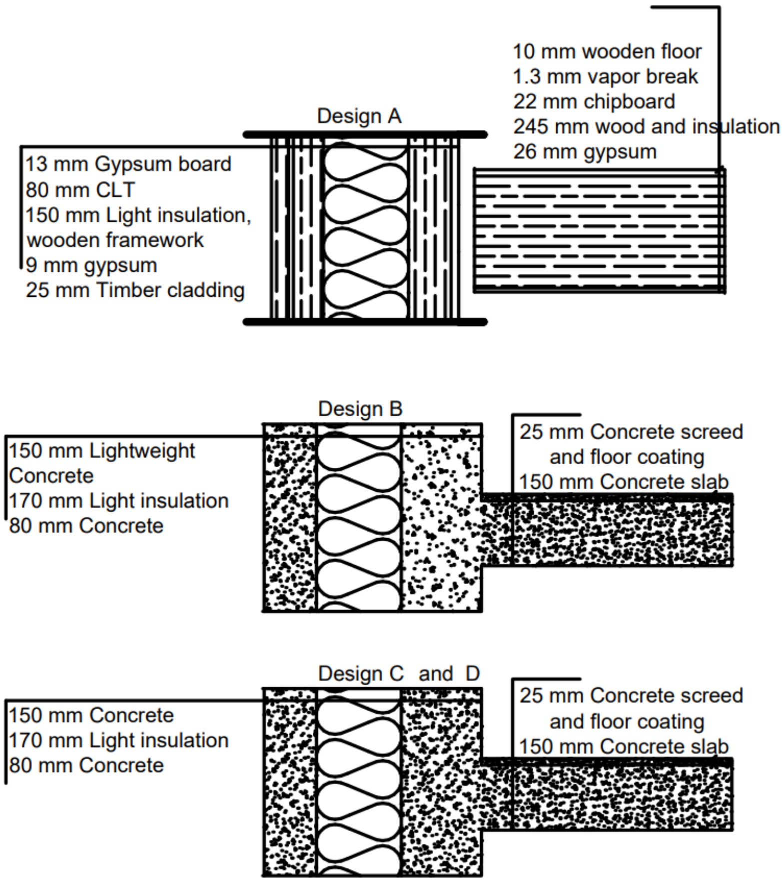

Figure 7: Structural design types of the case studies showing thermal mass variations

The internal walls were consistent across structures A, B, and C, comprising 30 mm of light insulation and 52 mm of gypsum. The internal wall for structure D consisted of a single layer of concrete 300 mm in width.

3 Results

The results are presented in the same order and categories as the methodological components described in Chapter 3. The findings are organized to demonstrate the effectiveness of the proposed simulation-based TMY generation method and to evaluate cooling system sizing through design day analysis and sensitivity studies.

3.1 TMY Generation Methods

3.1.1 Method Implementation

In line with the research questions, the starting assumption was that historical TMYs often fail to capture evolving climate and building performance requirements. Uncertainty in weighting factors for representative month selection in newer method variants can introduce region-dependent calibration choices and substantial processing effort. The selected months using ISO 15927-4 are shown in Table 9. In Table 10, all possible selection groups based on different temperature weighting factors (and consequently radiation, since their total must equal 1) are presented to support a more detailed comparison between methods. In the Estonian case studied here, no overlap was observed between the months selected by the simulation-based method and those selected by the climate-parameter-based approaches across the tested weighting-factor ranges. The results of traditional methods are analyzed together with the proposed method in the next section.

Table 9: Selected month/year using EN ISO 15927-4 method.

Month	1	2	3	4	5	6	7	8	9	10	11	12
Year	1999	2017	2016	2012	2011	2016	2013	2011	1998	1999	2019	1990

The new simulation-based method selects representative months by minimizing the statistical error of hourly energy use. In order to calculate the normalized versions of the statistical formulas mentioned in the methods, we need the annual heating and cooling needs. They are shown in Figure 8

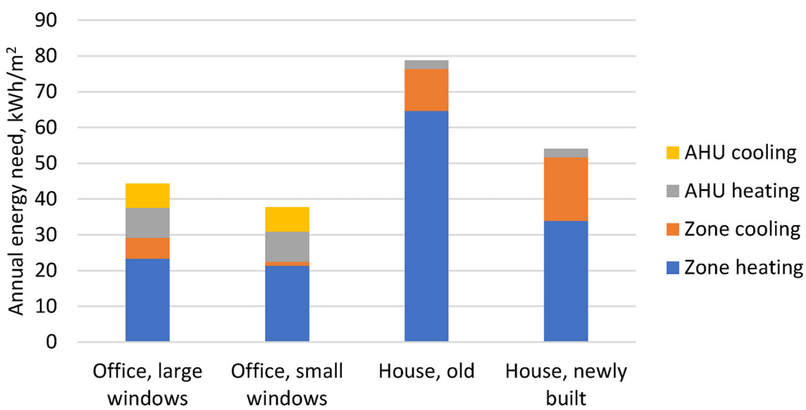

Figure 8: The annual heating and cooling needs for each building type used for normalization formulas, showing variations across different building configurations

The statistical methods used for TMY generation were evaluated based on their

Table 10: Top 3 ranked months using ISO 15927-4 method with weighting factors. The horizontal title is the weighting factor for temperature. The radiation weighting factor is subtracted from the temperature weighting factor.

Month\w	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
01	01-2019	01-2019	01-2017	01-1999	01-1999	01-2017	01-2017	01-2017	01-2017	01-2017	01-1999
	01-2004	01-2017	01-2008	01-1997	01-1997	01-1997	01-1997	01-1997	01-1997	01-1997	01-1997
	01-2008	01-2008	01-2007	01-1997	01-1997	01-1997	01-1997	01-1997	01-1997	01-1997	01-1997
02	02-2019	02-2019	02-2009	02-2009	02-2009	02-2009	02-2013	02-2013	02-2013	02-2013	02-2013
	02-2009	02-2009	02-2009	02-2009	02-2009	02-2009	02-2013	02-2013	02-2013	02-2013	02-2013
	02-2017	02-2017	02-2017	02-2017	02-2017	02-2017	02-2013	02-2013	02-2013	02-2013	02-2013
03	03-2016	03-2016	03-2016	03-2012	03-2012	03-2012	03-2012	03-2012	03-2012	03-2012	03-2012
	03-2019	03-2019	03-2019	03-2012	03-2012	03-2012	03-2012	03-2012	03-2012	03-2012	03-2012
	03-2012	03-2012	03-2012	03-2004	03-2004	03-2004	03-2004	03-2004	03-2004	03-2004	03-2004
04	04-2016	04-2016	04-2016	04-2016	04-2016	04-2016	04-2016	04-2016	04-2016	04-2016	04-2016
	04-2012	04-2012	04-2012	04-2012	04-2012	04-2012	04-2012	04-2012	04-2012	04-2012	04-2012
	04-2006	04-2006	04-2006	04-2006	04-2006	04-2015	04-2015	04-2015	04-2015	04-2015	04-2015
05	05-2020	05-2020	05-2020	05-2020	05-2020	05-2020	05-2020	05-2020	05-2020	05-2020	05-2020
	05-1990	05-1990	05-1990	05-1990	05-1990	05-2008	05-2008	05-2008	05-2008	05-2008	05-2008
	05-2008	05-2008	05-2008	05-2008	05-2008	05-2011	05-2011	05-2011	05-2011	05-2011	05-2011
06	06-2020	06-2005	06-2005	06-2013	06-2002	06-1997	06-1997	06-1997	06-1997	06-1997	06-1997
	06-2005	06-2005	06-2016	06-2016	06-2016	06-1997	06-1997	06-1997	06-1997	06-1997	06-1997
	06-2013	06-2013	06-2013	06-2013	06-2013	06-1997	06-1997	06-1997	06-1997	06-1997	06-1997
07	07-2008	07-2008	07-2006	07-2008	07-2006	07-2006	07-2006	07-2005	07-2005	07-2005	07-2005
	07-2017	07-2017	07-2003	07-2003	07-2003	07-2003	07-2003	07-2003	07-2003	07-2003	07-2003
	07-2003	07-2003	07-2018	07-2018	07-2018	07-2018	07-2012	07-2012	07-2012	07-2012	07-2012
08	08-2020	08-2019	08-2018	08-2004	08-2016	08-2016	08-2016	08-2016	08-2016	08-2016	08-2016
	08-2019	08-2016	08-2018	08-2004	08-2016	08-2016	08-2016	08-2016	08-2016	08-2016	08-2016
	08-2018	08-2018	08-2018	08-2018	08-2018	08-2016	08-2016	08-2016	08-2016	08-2016	08-2016
09	09-2015	09-2015	09-2015	09-2003	09-1998	09-1998	09-1998	09-1998	09-1998	09-1998	09-1998
	09-2020	09-2020	09-2020	09-2003	09-2003	09-2003	09-2003	09-2003	09-2003	09-2003	09-2003
	09-2016	09-2016	09-2016	09-2003	09-2003	09-2003	09-2003	09-2003	09-2003	09-2003	09-2003
10	10-2019	10-2019	10-2012	10-2012	10-2012	10-2012	10-2012	10-2012	10-2012	10-2012	10-2012
	10-1997	10-1997	10-1997	10-1999	10-1999	10-1999	10-1999	10-1999	10-1999	10-1999	10-1999
	10-1999	10-1999	10-1999	10-1999	10-1999	10-1999	10-1999	10-1999	10-1999	10-1999	10-1999
11	11-2014	11-2014	11-2014	11-2014	11-2014	11-2014	11-2014	11-2014	11-2014	11-2014	11-2014
	11-2009	11-2009	11-2009	11-2009	11-2009	11-2009	11-2009	11-2009	11-2009	11-2009	11-2009
	11-2020	11-2020	11-2020	11-2020	11-2020	11-2019	11-2019	11-2019	11-2019	11-2019	11-2019
12	12-2016	12-2016	12-2016	12-2016	12-2016	12-2016	12-2016	12-2016	12-2016	12-2016	12-2016
	12-1990	12-1990	12-1990	12-1990	12-1990	12-1990	12-1990	12-1990	12-1990	12-1990	12-1990
	12-2014	12-2014	12-2014	12-2020	12-2008	12-2008	12-2008	12-2008	12-2008	12-2008	12-2008

performance in minimizing the error between the duration curves of the generated TMY and the average of 31-year simulation results. The methods included Mean Absolute Error normalized by Annual Energy (MAE_AE), Mean Squared Error normalized by Direct Normal Radiation (MSE_DR), Mean Squared Error normalized by Annual Energy (MSE_AE), Root Mean Squared Error normalized by Direct Normal Radiation (RMSE_DR), R-squared, and Finkelstein-Schafer statistic. Among the evaluated statistical methods for TMY generation, Mean Squared Error normalized by Annual Energy (MSE_AE) demonstrated superior performance across all reference building types. The deviation analysis revealed that MAE_AE, MSE_AE, and RMSE_DR had acceptable performance, with the latter two achieving heating need deviations not higher than 1% for all reference buildings.

However, RMSE_DR showed cooling need deviations ranging from -9% to 10%, while MSE_AE provided more consistent values ranging between 3% and 6%. The MSE_AE method also provides higher values during the cooling period and similar or lower figures during winter, which aligns with global warming trends that continuously reduce energy demand during winter and increase demand during summer in the Estonian context.

As seen from Table 12, the **MSE_AE** method selected some months with a low ISO 15927-4 ranking, particularly in transition months with simultaneous heating and cooling needs. This reflects the complexity of identifying the most suitable TMY month during these periods. In ISO 15927-4, wind speed is used as a secondary selection criterion among the three candidates with the lowest total F.S. ranking, whereas the simulation-based methods do not apply this final wind-based filtering step. A detailed overview of annual cooling and heating needs per method together with average yearly need of 31 years simulation results are presented in Figure 9 and Figure 10.

Table 11: The deviation value of simulation results based on generated TMYs compared to the average of 31-year simulations

Building	**ISO 70-2000**		**ISO 90-2020 + WF**		**MSE_DR**		**MAE_AE**	
	Heat	Cool	Heat	Cool	Heat	Cool	Heat	Cool
Office – Big windows	-2%	-25%	-5%	0%	-2%	9%	-3%	-3%
Office – Small windows	-2%	-32%	-5%	-5%	-2%	5%	-4%	-2%
House – Old	5%	-35%	-3%	-7%	-1%	8%	-1%	-4%
House – New	4%	-24%	-3%	-4%	0%	9%	-2%	-5%
Building	**MSE_AE**		**RMSE_DR**		**ISO 90-2020**		**Finkelstein**	
	Heat	Cool	Heat	Cool	Heat	Cool	Heat	Cool
Office – Big windows	1%	6%	1%	-1%	-6%	-1%	-8%	-2%
Office – Small windows	0%	4%	0%	-9%	-6%	-4%	-9%	0%
House – Old	-1%	4%	-1%	10%	-4%	-13%	-3%	4%
House – New	-1%	3%	-1%	7%	-5%	-9%	-5%	0%

Table 12: Selected months using different statistical methods (YYYY(rank)). The ISO 15927-4 methods use wind speed as a final selection criterion among the three candidates with the lowest total F.S. ranking, whereas the simulation-based methods rank months solely by statistical deviation.

Month	**ISO 15927-4**	**ISO 15927-4 + weight**	**MAE_AE**	**MAE_DR**	**MSE_AE**	**MSE_DR**	**RMSE_DR**	**R Squared**	**Finkelstein Schafer**
Jan	1999(2)	1999(2)	2017(5)	2017(5)	1999(2)	2017(5)	1999(2)	2003(8)	2000(4)
Feb	2017(3)	2017(3)	1998(6)	1998(6)	1998(6)	1998(6)	1998(6)	1990(11)	2017(3)
Mar	2016(1)	2016(1)	2004(3)	2004(3)	2004(3)	1998(11)	2004(3)	2005(12)	2004(3)
Apr	2012(2)	2006(3)	2007(4)	2007(4)	2018(12)	2012(5)	2018(12)	2000(14)	2007(4)
May	2011(3)	2011(3)	2003(10)	2003(10)	2009(7)	1992(6)	2011(3)	1991(12)	2003(10)
Jun	2005(1)	2005(1)	2005(1)	2005(1)	2005(1)	2005(1)	1997(10)	1993(12)	1997(10)
Jul	2013(2)	2013(2)	2012(3)	2012(3)	2012(3)	2012(3)	1997(7)	2001(11)	2012(3)
Aug	2011(3)	2011(3)	1991(4)	2001(5)	2013(6)	1991(4)	2001(5)	1998(11)	1991(4)
Sep	1998(2)	2003(3)	2012(8)	2012(8)	1995(4)	1997(11)	2012(8)	1993(12)	2012(8)
Oct	1999(3)	1999(3)	2014(4)	2014(4)	2014(4)	2014(4)	2014(4)	2002(11)	2014(4)
Nov	2014(1)	2014(1)	2014(1)	2014(1)	2014(1)	2014(1)	2014(1)	1993(11)	2003(6)
Dec	1990(2)	2014(3)	1994(5)	1994(5)	1994(5)	1994(5)	1994(5)	2006(12)	1994(5)

Traditional TMY methods based on climate parameters at best, can result in energy use deviations exceeding 5% for heating and 7% for cooling when compared to long-term simulation results. These deviations are particularly problematic in the context of climate change, where the Estonian TMY created based on data from 1970 to 2000 shows drastically lower cooling needs during summer compared to more recent data. The proposed simulation-based method, however, achieves significantly lower deviations, with an average of 1% for heating and 4% for cooling needs across different building types. This demonstrates the method's effectiveness in capturing the evolving climate and building performance requirements, making it a more reliable option for TMY generation in the context of climate change. The load duration curve analysis of simulation results for the newly built single-family house model, as indicated in Figure 11, demonstrates that the cooling/heating needs curves resulting from TMYs are qualitatively close to the 31-year curve, providing fundamental validation that the process is implemented correctly and results are relevant. This basic validation is very important every time the method is used, to make sure that there is no major flaw in any step of the implementation.

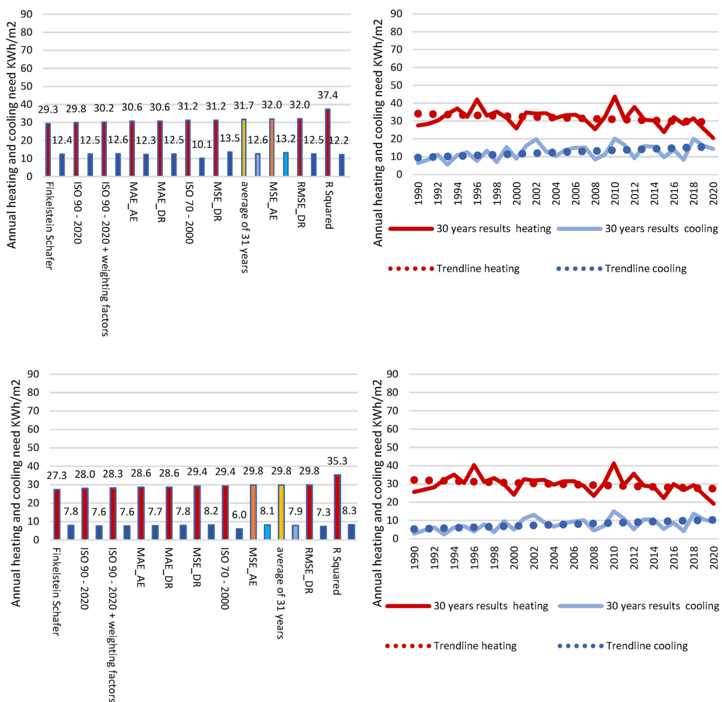

Figure 9: Office building annual heating and cooling needs in detail, comparing large windows (upper) and smaller windows (lower) configurations

Additional validation through cooling degree hours and heating degree days analysis presented in Figure 12 showed that the energy simulation-based method (MSE_AE) has the closest heating degree days and cooling degree hours values to the average of 31 years of simulation, further confirming its superior performance.

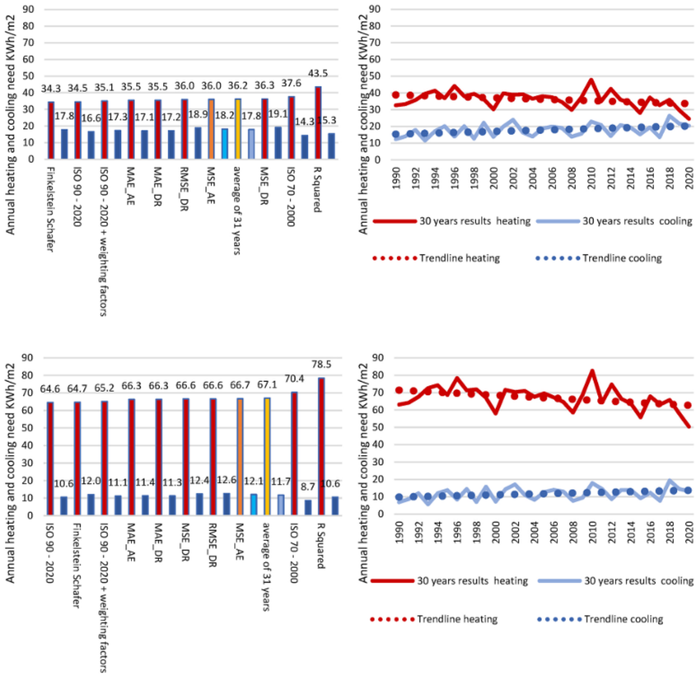

Figure 10: Single-family house building annual heating and cooling needs in detail, comparing newly built houses (upper) and old houses (lower)

3.1.2 TMY Methods Comparison Summary

The comparative analysis demonstrated that the method suggested in this research has lower deviations than traditional methods. The EN ISO 15927-4 method had the highest average deviation of 5% for heating and 7% for cooling, followed by the same method with weighting factors varying by 4% for heating and cooling. However, the proposed simulation-based method achieved the lowest average deviation within 1% for heating and, on average, 4% for cooling (Publication I).

Temperature and direct normal radiation for selected TMYs are also shown in Figure 14 and Figure 15. Comparing the monthly average values, the climate data does not differ significantly between different options. But in a more detailed view, specifically in transition months, the daily fluctuations and hourly values of the climate parameters differ drastically.

3.2 Design Day Generation and Risk-Level for Sizing

3.2.1 Design Day Generation method results

The design day parameters generated using ASHRAE are presented in Table 13 [28]. An illustration for July is given in Figure 16 (with calculated enthalpy instead of wet-bulb temperature) to facilitate comparison between risk levels. According to ASHRAE, the required parameters are daily minimum and maximum dry-bulb temperature (DB), wet-bulb temperature (WB), and wind speed [28]. These parameters were calculated for risk levels of 0.4%, 2%, 5%, and 10%, representing the frequency of occurrence of extreme conditions. The 0.4% risk level corresponds to the strictest conditions, while

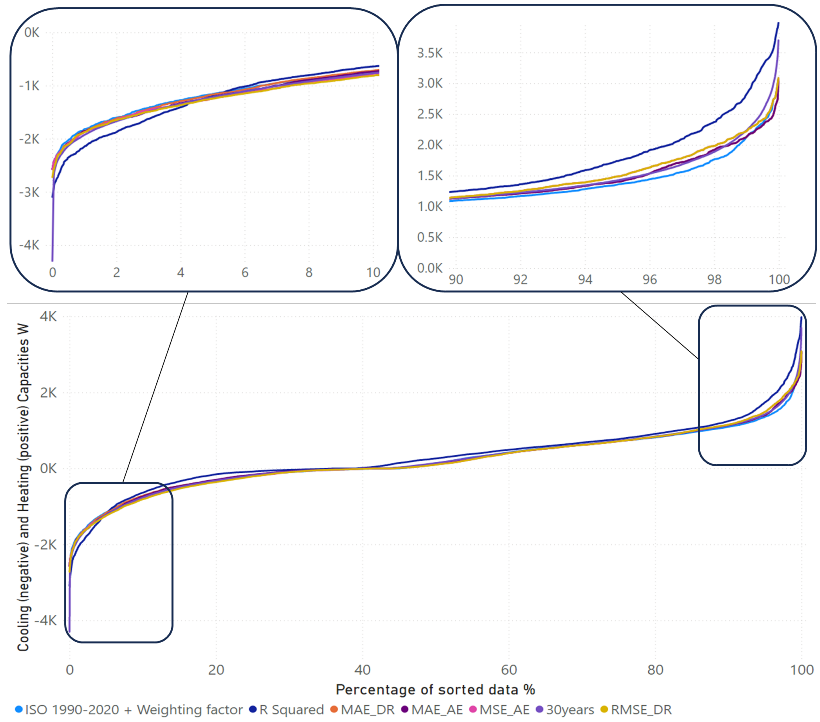

Figure 11: Cumulative Distribution Curve of the newly built single-family houses' resulting cooling/heating capacities for selected methods from simulations using different typical meteorological years

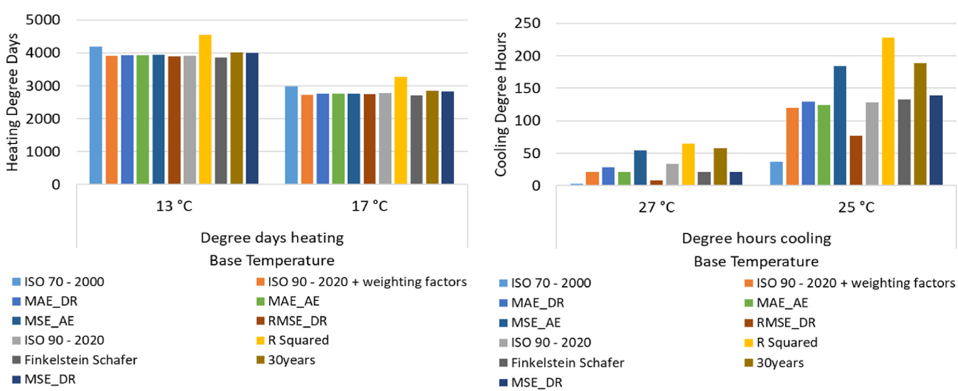

Figure 12: Heating Degree Days (HDD) and Cooling Degree Hours (DH) for TMYs together with other climate data

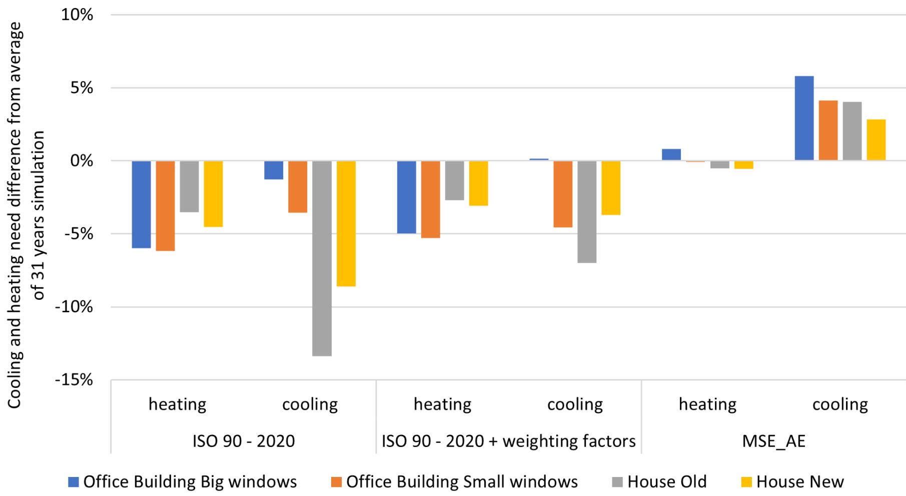

Figure 13: Energy needs deviation comparison between the ISO 15927-4 method, adjusted ISO 15927-4 method and the suggested method

the 5% level reflects more moderate scenarios. The maximum dry-bulb temperature in July reaches 29.8°C for the 0.4% risk level, compared to 28.2°C and 26.4°C for the 2% and 5% levels, respectively. The 10% level has the lowest value at 24.6°C. Wet-bulb temperatures show less variation across risk levels, with a maximum value of 22.4°C for the 0.4% risk level, underlining this parameter's relative stability in the ASHRAE method. IDA ICE calculates radiation in the ASHRAE method generically [53], using location-specific and atmospheric data, and this parameter does not vary between risk levels. The design day parameters based on ISO 15927-2 are listed in Table 14 [10], and the July design day is illustrated in Figure 17. Unlike the ASHRAE method, where dry-bulb and wet-bulb temperature trends align logically across risk levels, the ISO method yields results where critical days show discrepancies, such as reversed radiation trends. For example, while the mean dry-bulb temperature increases from 10% to 0.4% risk levels, the radiation data does not follow the same trend, with some risk levels showing lower radiation for stricter thresholds. The total radiation on the horizontal surface using both methods is shown in Figure 18.

Table 13: ASHRAE design day parameters by month. DB Max and DB Min denote daily maximum and minimum dry-bulb temperatures (°C), WB denotes wet-bulb temperature (°C), and Wind is given in m/s [28].

Month	**Wind**	**0.4% strictest**			**2% strict**			**5% moderate**			**10% moderate**		
	m/s	DB Max	DB Min	WB	DB Max	DB Min	WB	DB Max	DB Min	WB	DB Max	DB Min	WB
1	4.6	6.3	1.7	5.8	5.0	0.4	4.3	3.7	-1.9	2.7	3.2	-2.7	2.1
2	4.3	6.8	1.9	5.5	5.1	0.2	3.7	3.7	-1.2	2.8	2.9	-2.0	2.1
3	3.9	12.1	5.2	7.2	9.8	2.9	5.6	7.5	0.6	4.5	5.8	-1.1	3.5
4	3.3	17.1	11.9	12.0	13.6	6.6	10.2	11.4	4.5	8.1	9.4	2.1	6.5
5	3.1	27.4	18.4	18.3	24.4	14.5	16.5	21.6	12.6	14.3	19.4	10.3	12.8
6	2.1	30.2	23.2	22.3	27.7	20.7	20.8	25.3	18.3	19.3	23.1	16.1	17.8
7	4.9	29.8	24.1	22.4	28.2	22.5	20.5	24.7	20.7	19.9	24.6	18.6	18.9
8	2.9	29.9	23.6	21.1	27.6	21.3	19.7	25.2	18.9	18.8	22.9	16.6	17.6
9	2.3	24.3	17.6	18.3	21.3	14.6	16.6	19.2	12.5	15.7	17.0	10.9	14.4
10	6.3	16.3	8.8	13.8	14.2	6.9	12.4	12.1	5.2	10.8	10.5	3.7	9.3
11	5.1	11.8	5.0	8.3	9.6	3.0	7.2	8.1	1.7	5.9	6.8	0.3	4.7
12	6.3	8.9	2.0	7.9	6.7	0.2	5.9	5.4	-1.5	4.7	4.2	-2.7	3.6

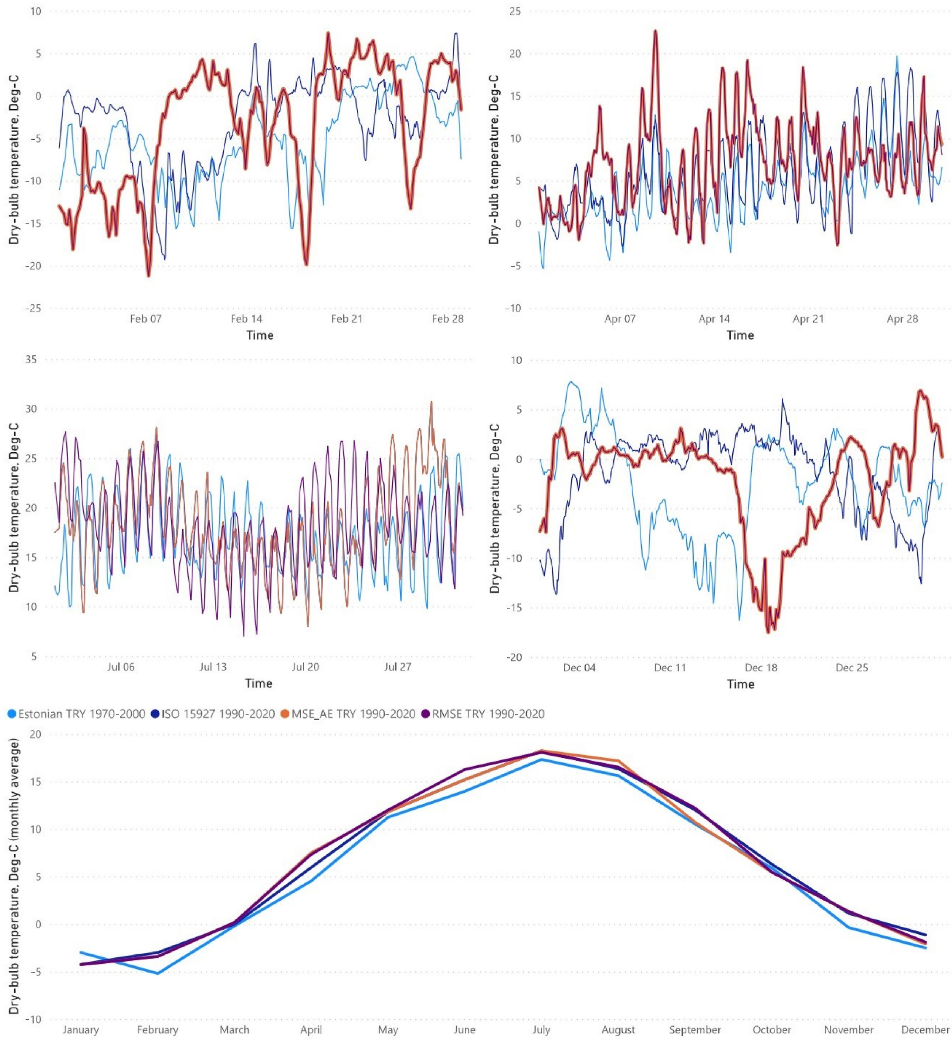

Figure 14: Dry-bulb Temperature for selected TMYs and selected months, showing hourly temperature values for February, April, July, and December

Table 14: Percentile-based design day parameters by month. DB Max and DB Min denote daily maximum and minimum dry-bulb temperatures (°C), WB denotes wet-bulb temperature (°C), and Wind is given in m/s.

Month	1% percentile, strictest				2% percentile, strict				5% percentile, moderate			
	DB Max °C	DB Min °C	WB °C	Wind m/s	DB Max °C	DB Min °C	WB °C	Wind m/s	DB Max °C	DB Min °C	WB °C	Wind m/s
1	8.3	1.3	7.2	6.0	7.2	1.2	6.0	6.0	4.4	1.2	3.2	6.0
2	10.1	0.5	8.4	3.3	8.4	1.0	5.2	5.4	5.2	-1.0	3.2	2.7
3	12.1	4.1	7.8	3.4	10.3	4.1	6.1	2.7	7.5	1.6	3.2	2.7
4	21.9	12.5	13.7	2.5	18.9	12.1	11.3	2.5	14.9	7.1	7.4	2.3
5	27.1	16.4	20.6	3.1	23.9	16.5	17.0	2.3	20.6	13.3	12.8	2.0
6	30.7	18.5	24.0	1.5	20.5	19.5	13.4	1.2	23.8	19.5	17.8	1.3
7	27.6	23.2	21.5	1.9	26.9	22.9	20.5	3.4	25.4	22.9	19.1	2.5
8	27.6	20.8	21.4	1.2	25.7	21.1	19.7	2.0	23.1	21.1	17.6	2.3
9	21.4	16.6	17.3	1.7	19.9	16.6	15.7	1.6	16.3	15.3	12.5	2.0
10	17.6	10.4	15.3	3.5	15.3	9.3	12.5	3.1	12.1	8.0	9.5	3.4
11	10.7	8.5	8.9	2.5	9.4	7.7	7.5	2.5	8.4	7.6	3.4	3.4
12	10.0	4.4	8.2	4.2	8.5	3.9	7.1	4.2	6.3	3.9	4.8	7.0

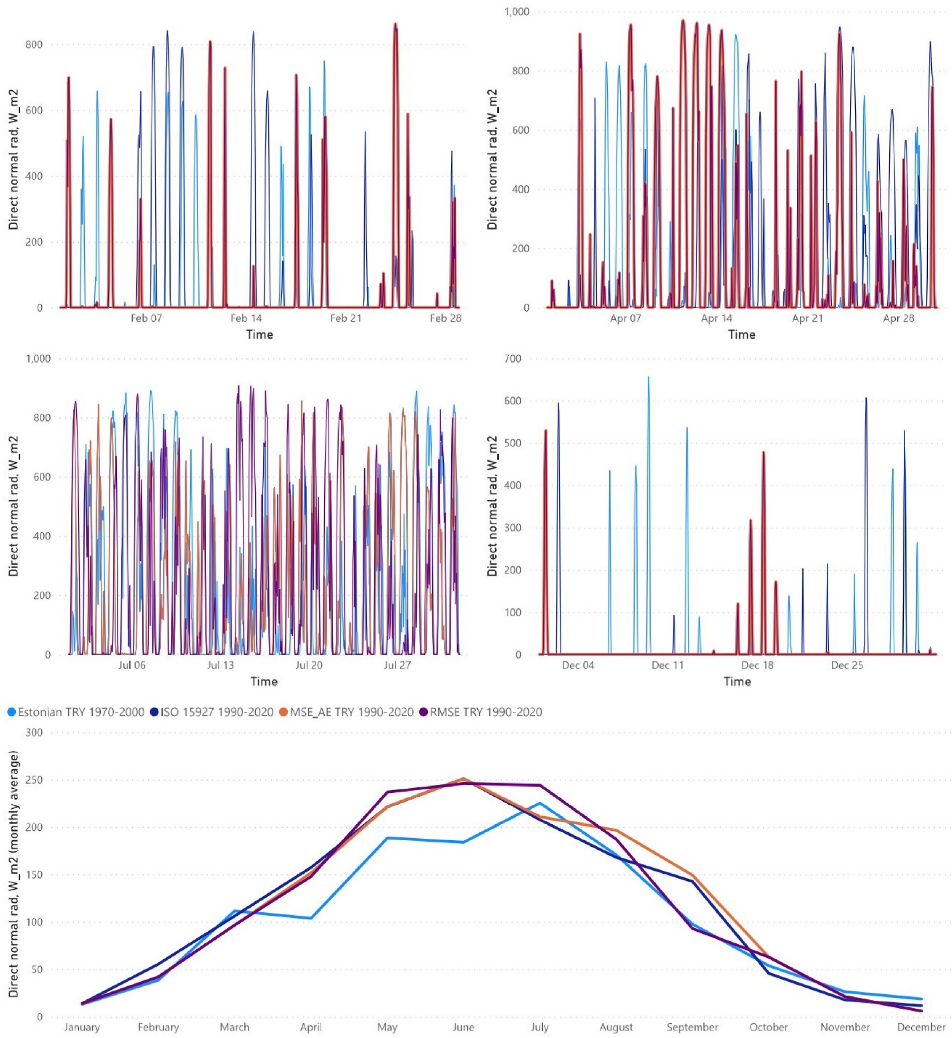

Figure 15: Direct Normal Radiation for selected TMYs and selected months, showing hourly direct normal radiation values for key months

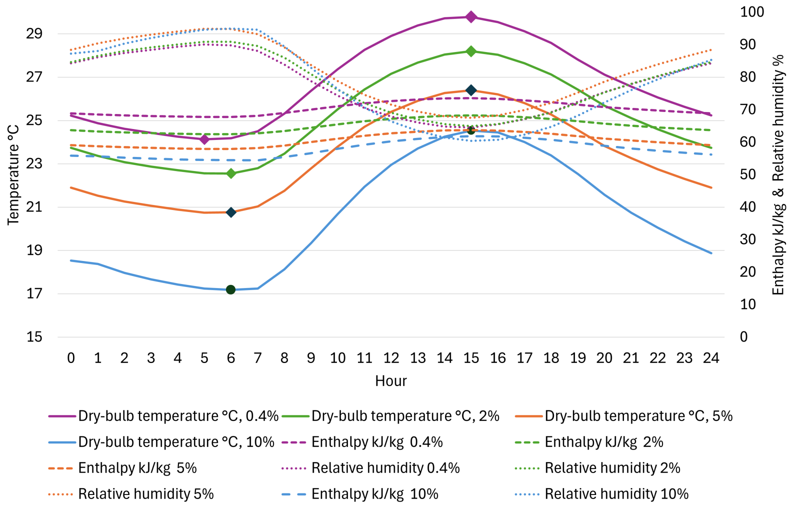

Figure 16: Dry-bulb air temperature and design wet-bulb temperature for July design days using ASHRAE method

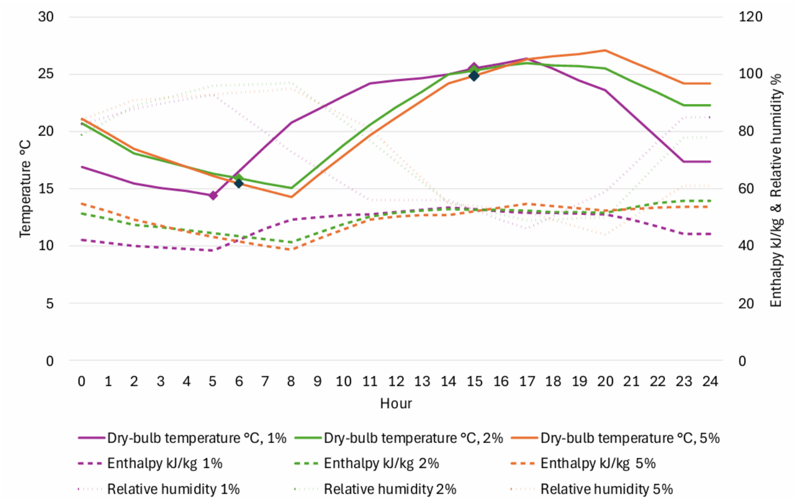

Figure 17: July design day based on ISO 15927-2 method showing parameter inconsistencies

The ASHRAE method produced more consistent design day parameters across different risk levels (0.4%, 2%, 5%, and 10%). The design days generated using ASHRAE showed logical progression of parameters, with maximum dry-bulb temperature in July reaching 29.8°C for the 0.4% risk level, compared to 28.2°C, 26.4°C, and 24.6°C for the 2%, 5%, and 10% levels respectively. Wet-bulb temperatures showed less variation across risk levels, with maximum value of 22.4°C for the 0.4% risk level, underlining the stability of this parameter which mainly affects air handling unit size. The inconsistencies in the ISO method were primarily attributed to the iterative process requiring wider error bands to identify suitable days. For example, the 1% risk level required approximately 50 expansion intervals, leading to broader possibilities for daily averages that could compromise the representativeness of selected design days. This fact is easier to understand by looking in Figure 19

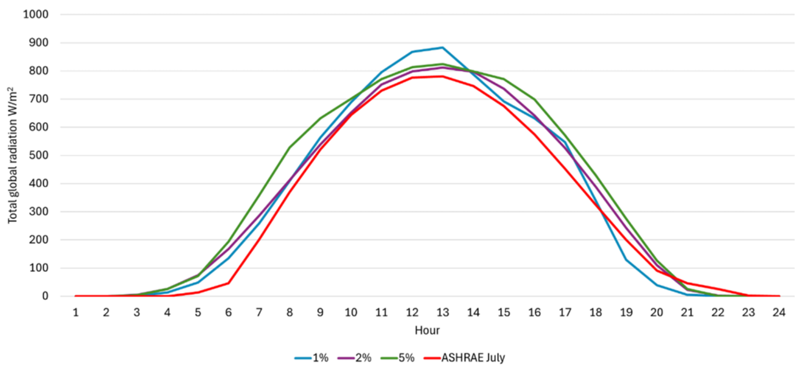

Figure 18: July Design Day total global radiation comparison between ISO methods and ASHRAE calculations

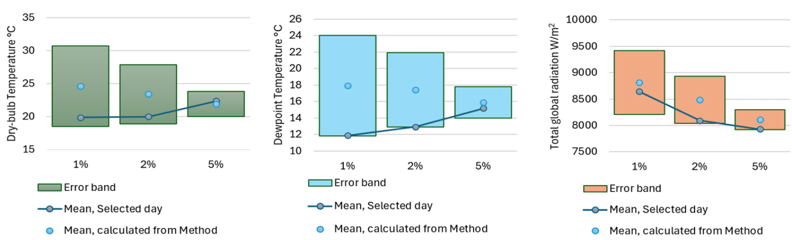

Figure 19: Mean value of parameters for Selected days for design day of July using ISO, blue dots represent the mean based on ISO, and Error bands are based on the number of intervals needed to find one day inside the error bands for different risk levels.

3.2.2 Cooling System Sizing Results

The cooling capacities designed using the design days based on the writer's interpretation from ISO 15927-2 [10] are shown in Figure 20. These results highlight several inconsistencies in the method's implementation and outcomes. For instance, in the BW No Shading South configuration, the cooling capacities remain almost unchanged across different risk levels (1%, 2%, and 5%), contrary to expectations where stricter risk levels typically result in larger cooling capacities. Similarly, in the BW Shading East configuration, the cooling capacities show unexpected patterns, such as lower capacities for stricter risk levels than more moderate ones. This counterintuitive result indicates potential issues in how the ISO method processes climatic parameters like solar radiation and temperature for risk based scenarios, which verify the claims regarding the method's inconsistency. Due to the inadequacy, under-specified implementation choices, and random-looking outcomes in the ISO method implementation, this method was excluded from the other sections of the results and conclusions.

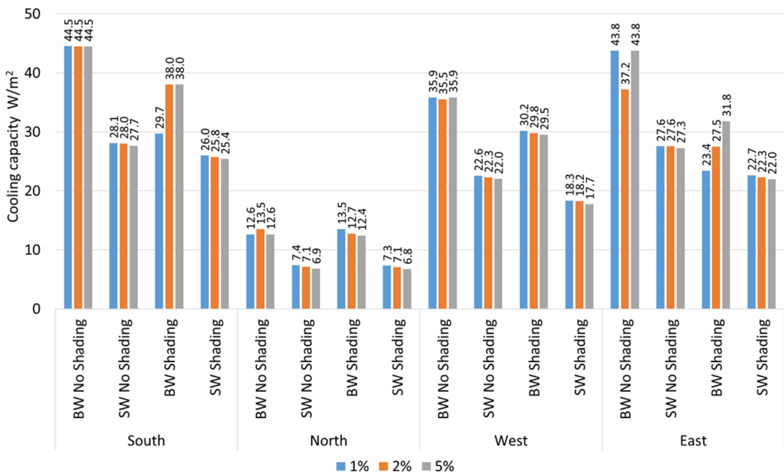

Figure 20: Cooling capacities sized using ISO 15927-2

The design cooling capacities derived from ASHRAE design day simulations are presented in Figure 21 and Figure 22. The results show clear and logical patterns related to building orientation and risk levels. South- and east-facing offices consistently required higher capacities than west- and north-facing zones, with the difference less pronounced in small-window buildings due to reduced solar heat gains. The impact of risk-level selection was evident across all orientations. For south-facing rooms without shading (big-window configuration), space cooling capacity decreased by approximately 14.3% between the 0.4% and 2% risk levels (from 40 W/m² to 34.5 W/m²) and further to 32 W/m² at the 5% risk level. East-facing rooms showed similar patterns, with approximately a 12% decrease between 0.4% and 2% levels and 18% between 0.4% and 5% levels.

The AHU system maintained relatively high capacities that varied mainly between risk levels, with little difference between window configurations or shading conditions. This was attributed to the design process being mainly dependent on wet-bulb temperature, which remained constant across different scenarios and varied only between risk levels according to the ASHRAE method.

A comparison scatterplot is shown in Figure 23 using cooling capacities resulting from both methods. The deviation of capacities is as big as 25%, with a correlation coefficient $R^2 = 0.93$ indicating a strong but inconsistent relationship. Figure 24 illustrates cooling demands by presenting a 24 hour simulation result for a representative day in July for the big window no shading model, where the temporal decoupling of peak demands is highlighted as the maximum cooling power for each component does not occur

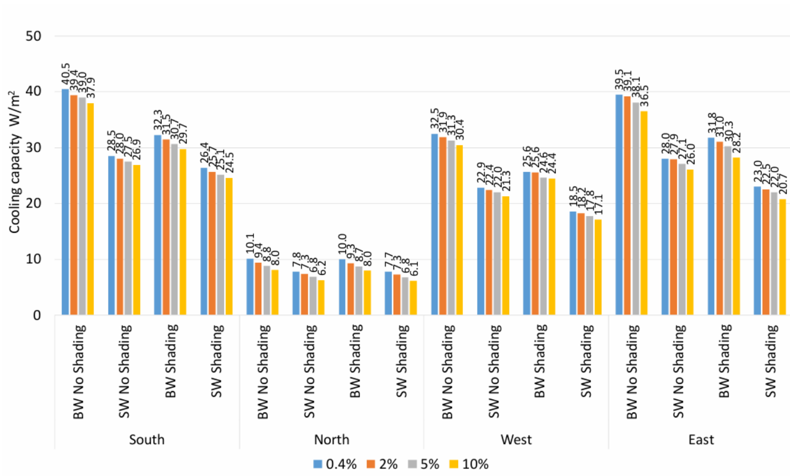

Figure 21: Zone cooling capacities (W/m²) for every building setting and risk level using ASHRAE method

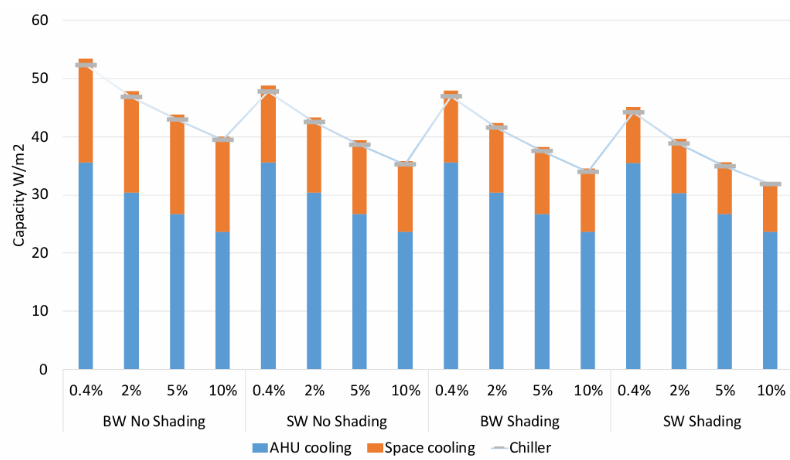

Figure 22: Total specific cooling capacities of cooling system components per net floor area for each building type

simultaneously.

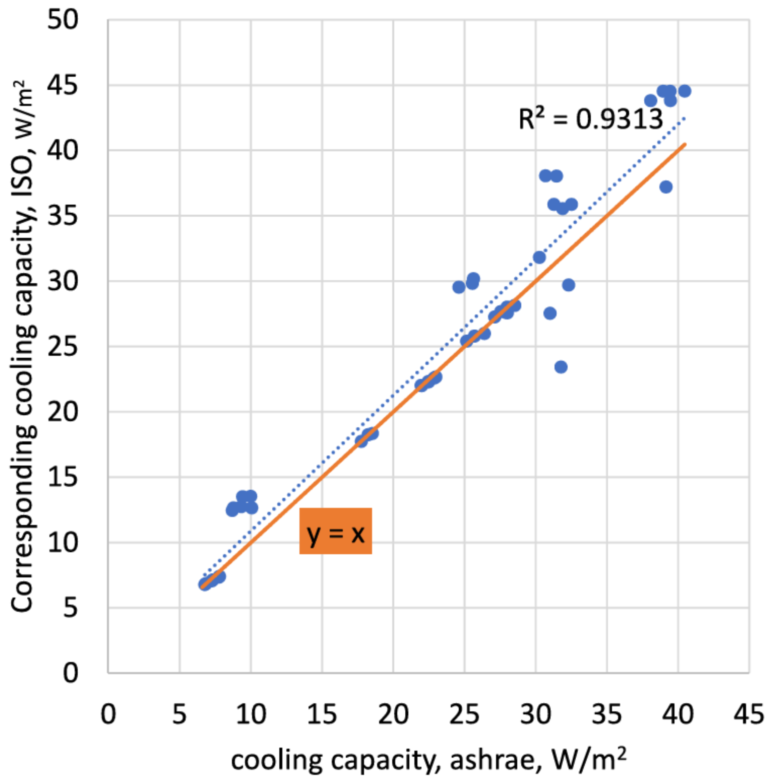

Figure 23: A comparison scatterplot for cooling capacities corresponding to the same building model sized using both methods, showing inconsistent but generally strong correlation ($R^2 = 0.93$) between the methods' results. (the chart excludes 10% results from ASHRAE for comparison)

3.2.3 Thermal Comfort Assessment

Figure 25 shows the maximum temperature during occupied hours for each zone over the 30-year simulation period. North-facing offices are more sensitive in terms of maximum temperature than the other orientations: all non-north zones remain below 25.6°C, whereas north-facing zones exceed 26°C. The difference between large- and small-window cases is limited. At the same time, stricter risk-factor selection has only a minor positive impact on maximum temperature, except for the small-window north zones where the middle-risk factor (2%) produced the highest maximum temperature.

Figure 26 shows the total number of hours above the 25°C threshold when cooling devices operate at maximum capacity for different room orientations and building types. Rooms without shading consistently experience the highest number of exceeded hours in all directions, and the difference between shaded and unshaded cases is larger for the large-window models. In general, the impact of risk-factor selection on exceedance remains small, which indicates that the sizing outcome is only weakly affected by the chosen risk factor. Excluding the north zone, the highest value occurs in the east-facing

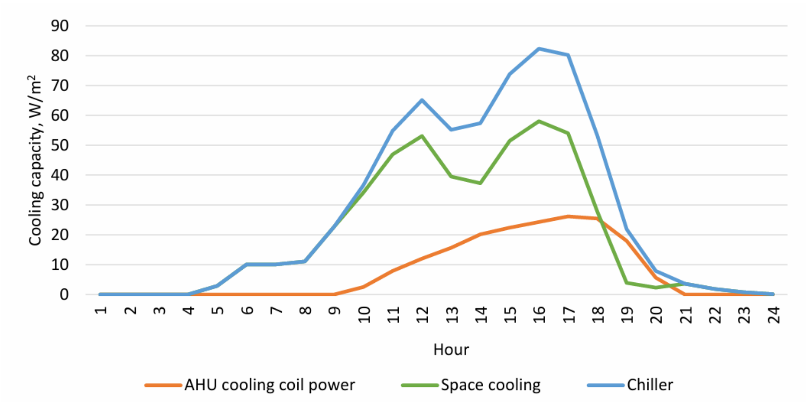

Figure 24: AHU, Space cooling and Chiller capacity profiles for an example day in July, showing temporal decoupling of peak demands

office with large windows and no shading, reaching 1533 h, which is approximately 1.5% of the total occupied hours over the 30-year period.

The graphs in Figure 27 compare solar radiation heat gains on the design day that produces the highest cooling capacity (15 June) with the annual radiation pattern for 2017 from the long-term simulations. Both cases refer to the north-facing office with large windows and no shading. The 2017 data indicate a sunny summer with peak gains in June due mainly to diffuse and indirect radiation typical of north-facing façades. In the underlying Sepúlveda study setup, the distance between the external façade and the surrounding building was fixed at 35 m, representing minimum availability of diffuse sky light and reflected light from surrounding buildings for the same obstruction angle. This helps explain why reflected solar radiation is limited in this case.

The cooling capacity for northern zones is between 8 and 15 W/m2, while in all other zones it is more than 15 W/m2, with an average above 20 W/m2. This lower cooling capacity makes the northern zones more vulnerable to temperature and radiation fluctuations and therefore more likely to experience elevated temperatures. Figure 26 indicates the maximum number of exceeded hours in a 30-day period for each combination. Although the north zone does not differ dramatically from the south- and west-facing zones, the east-facing zone shows much lower values, indicating a lower risk of overheating. The highest number of hours above 26°C (setpoint + 1) is below 3 h for all orientations except the north-facing zones. Since 3 h is below 1% of the occupied hours during a 30-day period (3.6 h), the ASHRAE design day method would theoretically satisfy the TAIL method requirements in most cases, although implementation and construction still affect the actual temperatures. For north-facing zones, additional effort such as long-term simulation or conservative rules of thumb may still be required. Another visible aspect is oversizing: except for the north-facing zone, which could be improved by smarter control strategies, the other zones show very similar excess-hour values for the ASHRAE risk levels of 0.4, 2, and 5% [28]. While EN ISO 15927-2 still needs general improvements [10], the standards currently offer limited means for achieving a more efficient design.

A comparison between AHU sizing strategies was conducted to assess the impact on indoor humidity conditions. In all models, the room unit capacities were kept constant,

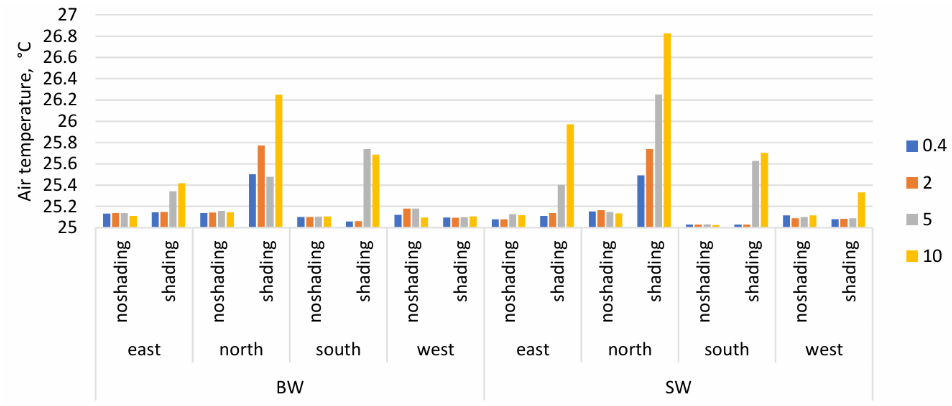

Figure 25: Maximum dry-bulb temperature in each zone during occupied hours over the 30-year simulation period (°C).

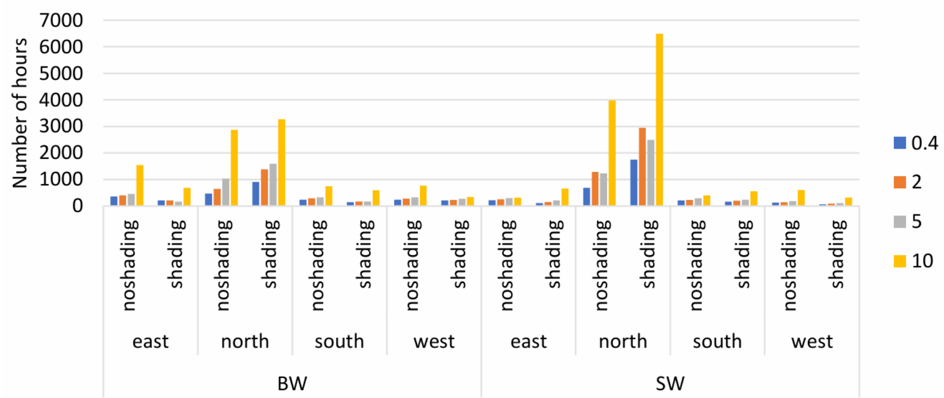

Figure 26: Total occupied hours with dry-bulb temperature above 25°C while cooling devices operate at maximum capacity over the 30-year simulation period (h).

based on sizing with the 10% risk level. The air handling unit cooling coil capacities, however, were varied and modeled according to the 0.4%, 2%, and 5% design risk levels. The dew point distribution curve and comparison for a representative hot July month are illustrated in Figure 29. The results indicate that under normal summer conditions, all three sizing approaches maintain similar dew point profiles. The dew point temperatures only diverge when outdoor enthalpy reaches exceptionally high levels and the AHU coil cooling capacity becomes a limiting factor. This is evident in the short periods where the 0.4% sizing results in slightly lower dew point values, visible as downward spikes in the difference plots. Figure 29 confirms that nearly all dew point temperatures in all three models fall below the critical 17°C threshold, with minimal deviation, especially in the 15–17°C range. While the 0.4% model did reduce dew point temperature more significantly during short peak events, the difference in overall humidity control between 0.4%, 2%, and 5% models remained minimal and the total number of hours exceeding 17°C is limited. Given that dew point temperature spikes occurred only during short periods of extreme outdoor enthalpy, and all sizing strategies maintained acceptable indoor humidity levels for the majority of the time, the findings suggest that 5% AHU sizing is sufficient in most practical cases, even for condensing room units.

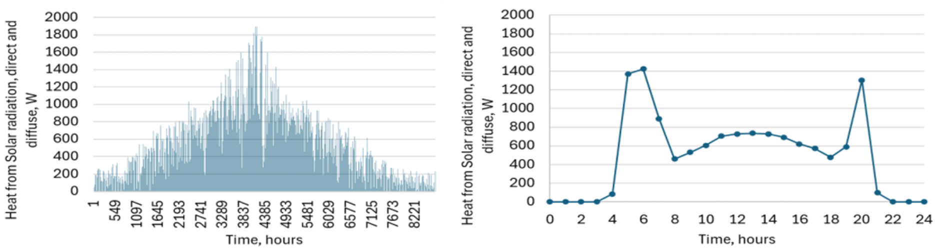

Figure 27: Solar radiation heat gains for the north-facing office with large windows and no shading: design day with the highest cooling capacity (right) and annual 2017 radiation profile from the long-term simulation (left), both for the 0.4% risk level.

3.3 Sensitivity Study Results

The results of the articles that were the base for sensitivity analysis examination to reveal the impact of various building design parameters on cooling system sizing requirements in Northern European climates are presented in this section.

3.3.1 Internal Heat Gain Profile Analysis

The experimental analysis of internal heat gain profiles from four office buildings in Tallinn, Estonia revealed significant variations in cooling capacity requirements based on actual occupancy patterns versus standard schedules. The study selected five weekly profiles representing different occupancy intensities: two from EN 16798-1 standard and three from actual building measurements. The distribution of the data points is shown in Figure 30

The measurement point EM7 recorded an average of 0.12 kWh/(24h · m^2), closely matching EN 16798-1 reference values, while EM24 displayed substantially higher consumption at 0.28 kWh/(24h · m^2), representing overcrowded office conditions. These empirical profiles, as opposed to standard schedules, significantly affected cooling capacity requirements across all building orientations Publication V.

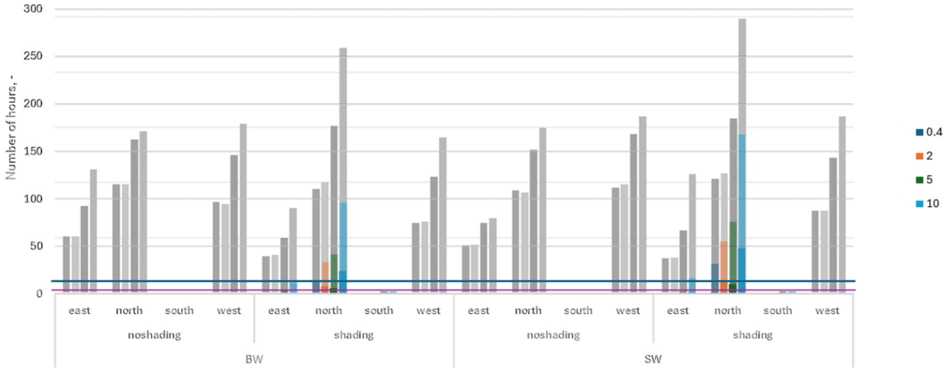

Figure 28: Maximum total number of exceeded hours in a straight 30-day period for each combination, resulting from 30 day rolling exceedance analysis. The total number of values exceeding 26 is shown with a starker color, exceeding 25.5 is illustrated with a faded color, and exceeding 25 is illustrated with grayscale. The blue line represents the 5% excess hour criterion [7] and the purple line shows 1% excess hour criterion [28].

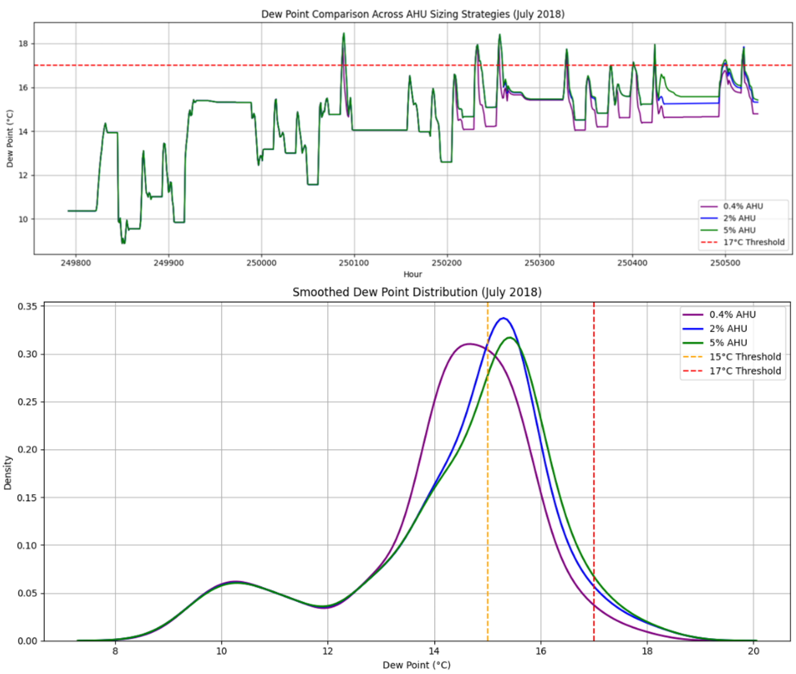

Figure 29: The dew point distribution curve and comparison for risk level impact analysis on AHU coil size. The KDE curves in the figure help visualize the minor differences across sizing strategies.

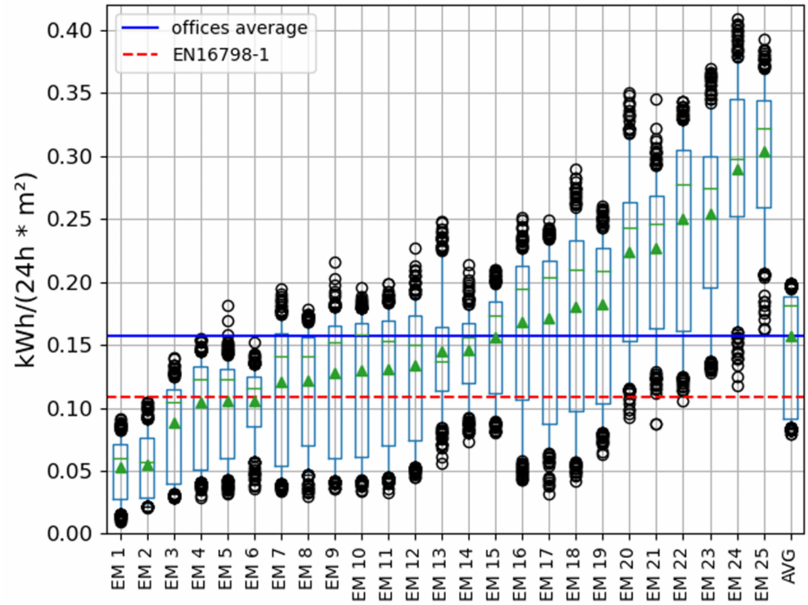

Figure 30: The distributions of data points in kWh/(24h · m^2) of each measuring point in the studied building

The heat balance for a representative warm week is shown in Figure 31. The figure shows that window heat gains and absorbed heat in internal blinds were the primary contributors to cooling loads, followed by internal heat gains from occupants and equipment. The analysis demonstrated that internal blinds effectively limited direct sunlight penetration, but transmitted and absorbed solar heat remained significant contributors to cooling demand.

Furthermore, the simulation results revealed that busy offices with high internal heat gains (EM24 profile) required substantially larger cooling systems compared to average profiles (EM7) and standard EN 16798-1 assumptions. The South and East offices consistently required larger cooling systems per square meter compared to Northern and Western offices due to solar heat gain patterns. The simulation results are summarized in Figure 32.

As it is indicated in Figure 33, the Northern office, where solar heat gains were minimal, the differences between various internal heat gain profiles were particularly evident. The EN 16798-1 suggested values showed significant gaps when compared to individual empirical profiles, although the difference was less pronounced when compared to the average of all measured profiles.

3.3.2 Thermal Mass Impact and calculation method Assessment

The comparative study of thermal mass effects using four different structural configurations (very light to very heavy) revealed that thermal mass provides moderate but not significant benefits for cooling system sizing. The thermal mass impact was most pronounced in the southern office, resulting in 5 W/m^2 or approximately 20 % difference between lightest (Structure A) and heaviest (Structure D) configurations. [56]. The comparison between long-term simulations and ASHRAE steady-state periodic method

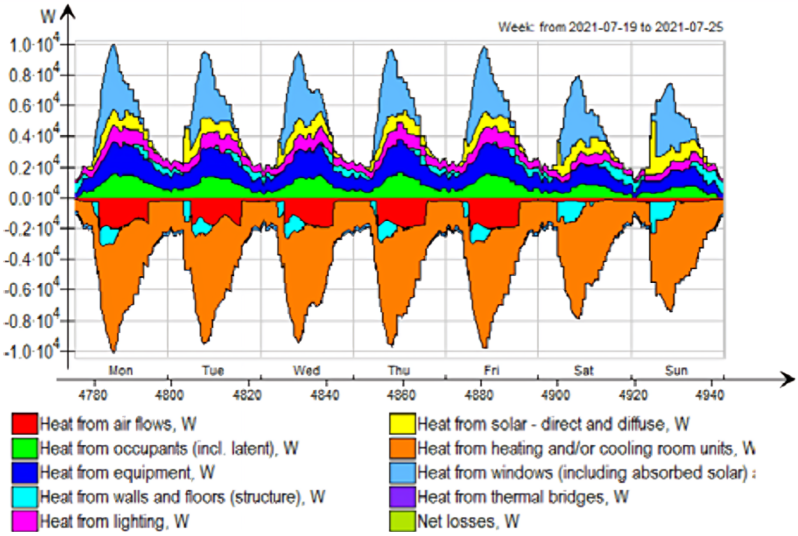

Figure 31: Heat balance chart of a warm week for the east-facing office, showing contributions from different heat sources for the EM24 profile, light construction, and large windows

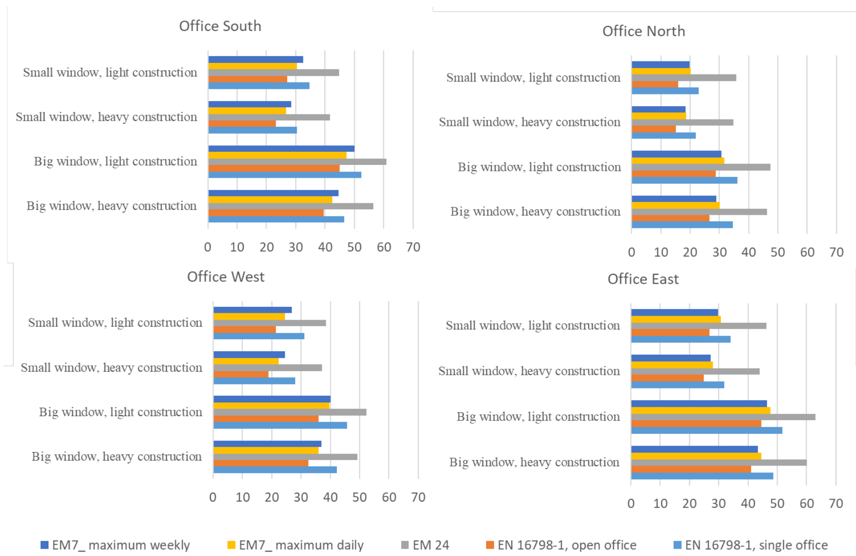

Figure 32: Cooling system size results for different scenarios and office orientations

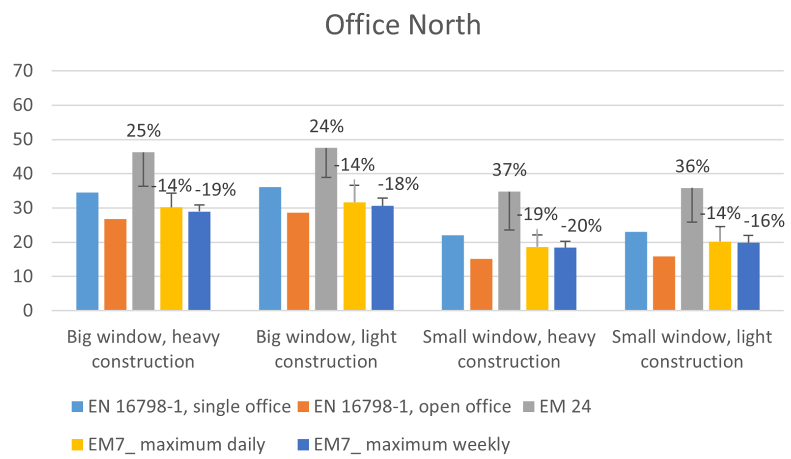

Figure 33: Cooling system size for the Northern office, magnifying differences between profiles and EN 16798-1 suggestions

showed that both approaches yielded fairly similar results. The steady-state method estimated values were within 1–4 W/m^2 range compared to long-term simulations, with variations depending on specific case study variables.

As shown in Figure 35, the operative temperature duration curves demonstrates that higher thermal mass resulted in lower average operative temperatures during cooling periods and reduced hours with temperatures exceeding thermal comfort thresholds. Buildings with lower thermal mass experienced higher numbers of hours with operative temperatures above 26°C, indicating inferior thermal comfort performance despite similar cooling system sizing.

When operative temperature requirements were considered, the importance of thermal mass became more apparent. Adjusted air temperature setpoints for compliance with EN 16798-1 showed that Structure A required 24.97°C while Structure D required 25.08°C, with the difference in designed cooling system size being more pronounced in long-term simulations.

3.3.3 Window Size and Orientation Impact

The analysis of window configurations revealed significant impacts on cooling system sizing. Window size changes from 25% to 58% Window-to-Wall Ratio (WWR) resulted in 35% larger cooling systems on average. However, the impact varied considerably by orientation, with window sizes having minimal effect on cooling capacities for north-facing offices due to lower solar irradiance impact Publication V, [56].

For efficiently insulated office buildings, the critical months for determining cooling system capacity were June, July, and August for North, East, and West offices, while September was critical for South-facing offices. This pattern resulted from solar radiation angles being lower during September compared to summer months, creating higher solar loads in autumn for south-facing spaces. The study showed that the combination of heavy thermal mass and smaller windows provided the most favorable conditions for reduced cooling demands.

The detailed analysis of critical design days revealed interesting patterns. For the

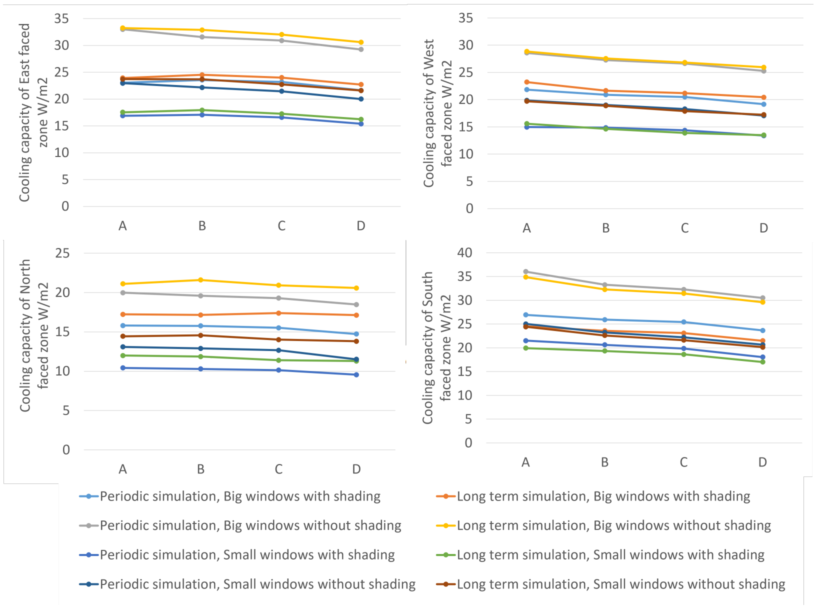

Figure 34: Cooling design capacities for different building bodies, window sizes, and shadings, showing thermal mass impact across configurations

East office, the peak cooling demand occurred on July 6, 2009, while for the South office, it occurred on September 9, 2019. The radiation and temperature patterns of these specific days, when compared to synthetic climate parameters as shown in Figure 36, revealed the importance of taking into account the actual weather variability in design loads.

3.3.4 Solar Radiation and Daylighting

The comprehensive analysis of solar radiation impacts on cooling system sizing and daylight provision demonstrated that solar gains through windows are the most critical factor for cooling system sizing in low- to medium-occupied offices. The study developed prediction methods based on Annual Incident Solar Radiation (AISR) that enable rapid facade optimization for balancing daylight and thermal comfort (Publication III).

The correlation analysis revealed strong relationships between Specific Cooling Capacity (SCC) and Window-to-Floor Ratio × g-value combinations, with correlation coefficients (R^2) exceeding 0.85 for most orientations and AISR conditions. South-oriented rooms showed the highest sensitivity to solar heat gains, while north-oriented rooms exhibited lower correlation due to reduced direct solar exposure (Publication III).

For thermal comfort control through cooling-capacity limitation, the analysis established maximum WFR×g-value combinations that prevent excessive cooling demands. The thermal comfort prediction accuracy was higher than daylight provision prediction accuracy, with 89.7% correct predictions on average; therefore, the rule of thumb provided in Publication IIIis sufficiently reliable for early-stage use.

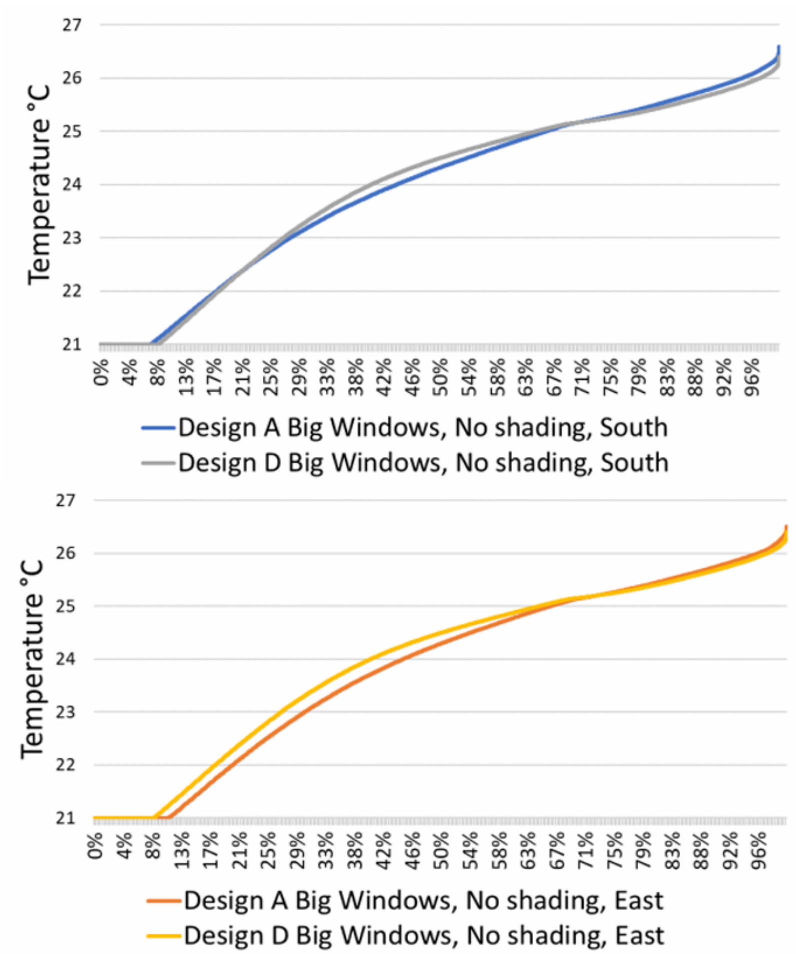

Figure 35: Duration curve for operative temperature in selected cases and offices, showing thermal mass effects on comfort

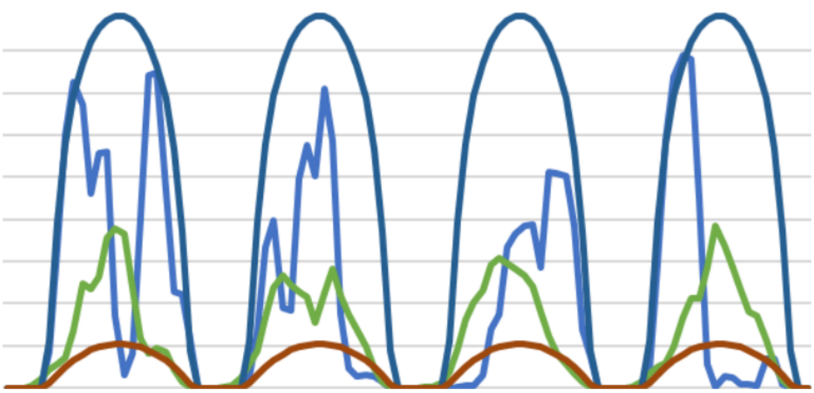

Figure 36: Comparative climate parameters for July simulation results comparing long-term actual weather with synthetic climate data

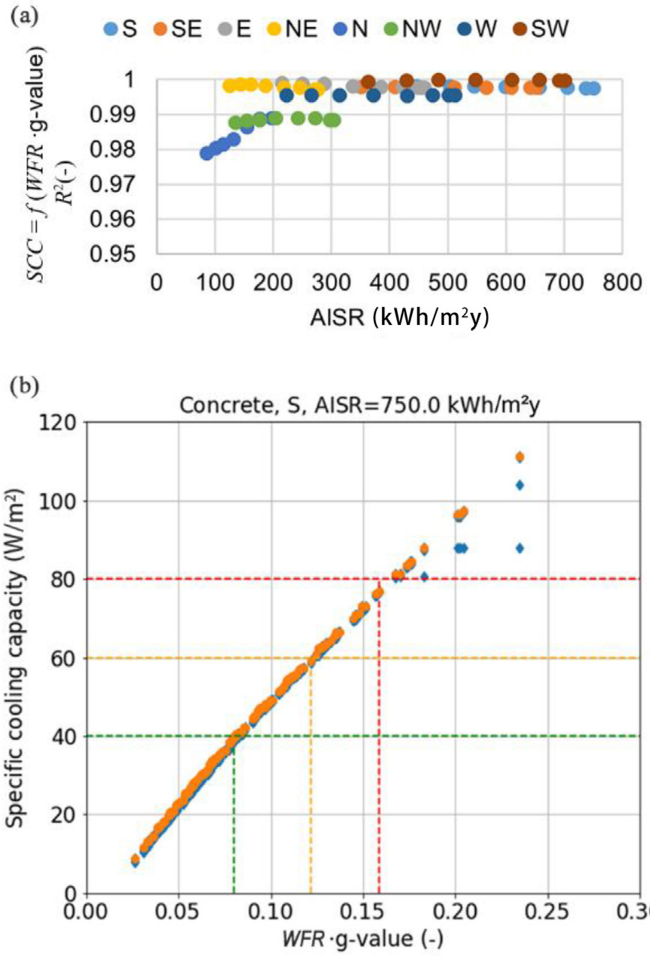

Figure 37: Correlation coefficient R^2 between SCC and WFR$\times$g-value for different AISR values and room orientations

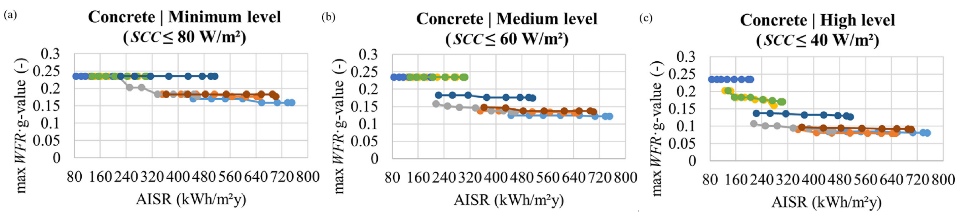

Figure 38: Maximum recommended WFR$\times$g-value depending on room orientation and accumulated AISR to achieve different levels of thermal comfort

3.3.5 Variable Importance Summary

The comprehensive sensitivity analysis across all studies revealed the following importance ranking for cooling system sizing parameters:

This ranking consolidates evidence from the five thesis publications, with direct factor-specific results mainly from Publications II–V and supporting weather-data context from Publication I (Publication I, Publication II, Publication III, Publication IV, and Publication V).

1. **Solar Gains / orientation (High Impact):** Solar radiation through windows emerged as the most critical factor, particularly for south and east-facing offices. The combination of window size, orientation, and solar heat gain coefficient dominated cooling load calculations (Publication III, Publication II, and Publication IV).

2. **Internal Heat Gains (Medium-High Impact):** Actual occupancy patterns and equipment loads significantly affect cooling requirements, with empirical profiles showing up to 35% higher cooling demands compared to standard assumptions (Publication V).

3. **Window Configuration (Medium Impact):** Window-to-wall ratio changes from 25% to 58% resulted in 35% larger cooling systems, but the impact varied significantly by orientation (Publication IVand Publication III).

4. **Thermal Mass (Medium-Low Impact):** Heavy construction provided up to 20% reduction in cooling capacity requirements, with benefits being most pronounced in south-facing offices. The impact was more significant when considering operative temperature criteria (Publication IV).

The investigation of representative months with varying weighting factors revealed that simulation-based selection sometimes identified months not highly ranked by any single climate parameter, confirming the complexity of the interactions between different design variables, Therefore its not always straight forward to name the most important climate parameters while wind is obviously less important according to literature and results of this paper.

4 Discussion

This chapter critically examines the limitations and challenges encountered in the research while identifying potential directions for future development. While the comprehensive analysis presented in previous chapters provides significant advances in building energy simulation and cooling system design, several constraints affect the generalizability and practical implementation of the proposed methods.

4.1 Research Limitations and Methodological Constraints

The study acknowledges several methodological limitations that influence the scope and applicability of the findings. The reliance on simplified occupancy schedules and building parameter assumptions may not fully capture the complexity of real-world operations. These models represent a limited scope of building types and operational patterns that may not be representative of all building categories and usage profiles. For practitioners who typically use standard assumptions based on EN 16798-1 guidelines, these limitations become particularly problematic in special buildings or busier offices that exceed original design occupancy levels, potentially leading to forced relocation or reduced user satisfaction.

The selection of reference buildings introduces potential bias in the results and limits the ability for generalization to other building types and configurations. While the study employed four building simulation models including non-residential and residential usage patterns, this limited selection may not adequately represent the full spectrum of building applications. The analysis used two office models with different window sizes to account for solar heat gain differences and two single-family homes representing different insulation levels, but this scope remains constrained for broader application and therefore it is important to select higher number and variety of reference building models.

Climate model limitations present significant challenges when applying the methods to future climate projections. A brief exploratory application indicated data-compatibility and uncertainty constraints that require cautious interpretation and further validation before broader design use [57]. Temporal and spatial limitations further constrain the methodology. The approach assumes fixed climatic characteristics without incorporating real-time adaptation capabilities, preventing consideration of dynamic climate variations and short-term fluctuations that can significantly impact building performance. The exclusion of urban microclimate effects represents another constraint, as urban canyons characterized by high obstruction levels pose challenges for designers. The exclusive consideration of direct and diffuse solar radiation components, without accounting for reflected radiation, may cause design recommendations to overestimate thermal comfort levels. In the Sepúlveda-based setup used in this thesis, the distance between the external façade and the surrounding building was fixed at 35 m, which represents minimum availability of diffuse sky light and reflected light from nearby surrounding buildings for the same obstruction angle.

An additional temporal limitation concerns the appropriateness of the 30-year period used for TMY generation in the context of accelerating climate change. There is a risk that using 30 years may be too long given the speed of current climate change trends, potentially incorporating outdated climate patterns that no longer represent current or future conditions. The accelerating pace of climate change may render older data within the 30-year period less relevant for contemporary building design. Further study is needed to investigate the use of shorter periods, such as 10 or 20 years, to find a more optimal choice of the period that better reflects current climate trends while maintaining sufficient statistical validity for TMY generation. Such studies would need to balance the competing requirements of capturing sufficient climate variability for statistical robustness while ensuring the data remains representative of current and near-future climate conditions.

Computational and practical limitations include the high computational intensity expected from the long-term simulation approach compared to original methods. Even with a limited range of test buildings, computational demands remain high, potentially limiting practical applicability for large-scale implementations or real-time applications. The TMY method's dependence on simulation data creates circular dependency where TMY accuracy depends on the accuracy of simulation tools and models used for generation. The complexity of input data requirements for simulations generated from climate model files further compounds these limitations.

Standard-related limitations emerged through the comparison of different approaches, particularly highlighting significant inconsistencies in ISO 15927-2 due to practitioner-dependent optional parameter selection. The study revealed inconsistent results between different risk levels in ISO-based methods, with unexpected patterns such as lower capacities for stricter risk levels than moderate ones. This is primarily because ISO 15927-2 treats each meteorological parameter (dry-bulb, global radiation, humidity) as an independent percentile without normalization or weighting, which can produce internally inconsistent combinations that misrepresent real joint extremes. For example, a 1% dry-bulb day may coincide with typically low radiation, leading to under-predicted solar gains. Future improvements to the ISO method should consider a unit-less normalization approach or weighting factors to ensure that the joint impact of different parameters is logically represented. Due to these inadequacies, under-specified implementation choices, and random-looking outcomes in ISO method implementation, this approach was partly excluded from sections of results and conclusions.

Furthermore, while not explicitly simulated, smart control strategies such as early activation or better utilization of building thermal mass represent promising directions for future research. These strategies could potentially allow for even lower design capacities while maintaining the same comfort range, demerging setpoints from target temperatures.

Additional scope limitations include uncertainty regarding internal heat gain variability and occupancy diversity. No cost-benefit analysis was conducted, limiting practical implementation guidance for practitioners who must balance performance improvements with economic considerations. While the research demonstrates technical feasibility and performance benefits, economic implications of implementing the proposed methods remain unexplored. Although the developed method has no geographical or climatological limits in principle, testing was limited to the Estonian humid continental climate (Dfb) with typical reference buildings.

4.2 Future Research Directions and Development Opportunities

Future research should focus on expanding the application of TMY methods to different climates beyond the Estonian context while investigating a more optimal length of historical weather data period. Investigation of the viability of solar radiation-based prediction methods in other climatic contexts and building types would validate the generalizability of proposed approaches and identify climate-specific adaptations. Development of automation tools for TMY generation represents a significant opportunity to streamline implementation processes, reduce computational demands, and improve accessibility for practitioners. Such automation should incorporate lessons learned about the importance of building-simulation-based approaches over traditional climate-parameter-based methods.

For design day generation method, future research should explore hybrid approaches combining strengths of different existing methods while addressing individual limitations. Developing new methods for design day generation represents a critical area, particularly given the limitations current risk level based generation and its effectiveness on thermal comfort has. Future methods should address under-specified parameter-selection procedures in current standards and provide more reliable thermal-comfort-based design guidance.

Future research should explore new methods or improved version of established methods for design day generation. This could lead to more comprehensive methods leveraging strengths of both ASHRAE and ISO 15927-2 standards while addressing individual weaknesses. Research extension should include non-condensing cooling systems that may have different performance characteristics and design requirements compared to systems analyzed in this study.

Development of comprehensive training materials and implementation guidelines would support adoption of proposed methods in practice, including best practices for different climate zones, building types, and design objectives.

Future research may even incorporate life cycle assessment methodologies to evaluate long-term environmental impacts of design decisions informed by proposed methods. The potential for integrating machine learning approaches with simulation-based methods should be explored, as advances in computational efficiency and algorithmic development may improve viability.

5 Conclusions

This research has developed and validated methods for improving building energy simulation accuracy through enhanced typical meteorological year (TMY) generation, design day development, and targeted sensitivity analyses. The work addresses critical gaps in current practice and provides concrete contributions to building performance simulation methodology, with direct applications for practitioners and implications for standards development.

5.1 Research Innovations and Findings

The research has produced one major innovation and three major analyses that collectively advance building energy simulation and cooling system design. The major innovation, a simulation-based TMY generation method, creates typical meteorological years that, when used in simulations, result in hourly cooling and heating needs with load distribution curves closest to those from long-term simulations using meteorological data. The method compares monthly energy simulation results to 31-year simulation results and uses statistical methods to select the optimal month/year combination among 31 possible choices, creating the TMY by combining those selected months.

The simulation-based TMY generation method represents a fundamental shift from traditional climate-parameter-based approaches, achieving significantly improved accuracy with deviations within 1% for heating and 4% for cooling, compared to 5% and 7%, respectively, for improved versions of the EN ISO 15927-4 method. This advancement eliminates the need to choose climate-parameter weighting factors through direct use of building simulation results for representative month selection, while indirectly incorporating all climate parameters through building performance simulation. The MSE_AE (Mean Squared Error normalized by Annual Energy) statistical method emerged as the optimal approach for the cold climate of Estonia, providing consistent deviation estimates across different building types and showing alignment with global warming trends. Another statistical method among those provided in the Methods may be suitable for other regions of the world.

The approach distinguishes itself by directly employing statistical tools on energy simulation results rather than climate parameters. Different weather conditions and climate parameter interactions are accounted for indirectly through their impact on simulation results. The method demonstrates geographic independence, as it is described without geographical boundaries and can be applied in any region to generate specific TMYs, though it was validated using the Estonian humid continental climate (Dfb) with typical reference buildings.

The comprehensive evaluation of design day generation methods provided definitive guidance for practitioners. The ASHRAE Fundamentals method demonstrated consistent and reliable results across all risk levels with logical parameter progression, while ISO 15927-2 exhibited fundamental inconsistencies and counterintuitive results, limiting its applicability for practitioners. The thermal comfort assessment revealed that risk level selection significantly affects system sizing but has minimal impact on actual thermal comfort outcomes. Specific recommendations emerged for different system components: 10% risk level for room units and 5% risk level for AHU systems ensure capability of achieving thermal comfort requirements and handle proper humidity control and system performance, while north-facing zones require additional design considerations due to higher overheating sensitivity. Although the simulations were conducted for the Estonian climate, the findings can be applicable to other cold or temperate regions (Dfb) with similar climatic conditions, such as parts of Northern Europe or North America.

The systematic analysis of building design parameters established a clear hierarchy of importance for cooling system optimization. Solar gains dominate the cooling load calculations through window orientation, shading, size, and solar heat gain coefficient effects. Internal heat gains showed medium-high importance, with empirical profiles demonstrating up to 35% higher demands compared to standard assumptions. Thermal mass provided medium impact with up to 20% cooling capacity reduction in south-facing offices, while window configuration changes from 25% to 58% window-to-wall ratio resulted in 35% larger cooling systems. A breakthrough in computational efficiency was achieved by providing rules of thumb through solar radiation-based prediction methods, demonstrating 57,000-fold speed improvements compared to traditional simulation approaches while maintaining acceptable accuracy for early design stages. While this study focused on methodological evaluation rather than optimization, future research should explore integrating these findings with parametric studies and statistical analyses to search for optimal solutions.

5.2 Practical Implementation Strategy of the Innovation

The implementation of simulation-based TMY generation follows a systematic three-phase approach. The preparation phase involves developing representative building models for local building stock with typical construction types, HVAC systems, and usage patterns, validated against measured performance data when available. Historical data collection requires gathering 30-year hourly weather data with quality assurance through outlier detection and gap filling, prepared in simulation-compatible format. The TMY generation phase conducts 30-year simulations for each representative building model, extracting hourly heating and cooling loads for each month and generating load duration curves for comparative analysis. Statistical analysis applies the MSE_AE method for representative month selection, comparing monthly load duration curves to 30-year averages and selecting months with lowest deviation for TMY assembly. The validation phase ensures quality through TMY representativeness verification using degree day analysis, comparison of TMY simulation results with long-term averages, and sensitivity analysis for different building types, accompanied by comprehensive documentation of methodology and assumptions for reproducibility.

The research findings demonstrate immediate applicability to northern European climates similar to Estonia, continental climates with significant seasonal variations, and cold climates experiencing emerging cooling requirements due to climate change. For application in different climates, adaptation requires recalibration of statistical methods for local climate patterns, adjustment of risk level recommendations based on regional thermal comfort standards, and validation using local building stock and usage patterns. The major research innovation with broader universal applicability is the simulation-based TMY generation methodology.

5.3 Practical Impact and Implementation Benefits

The developed methods demonstrate significant practical applicability extending beyond the original testing context. The simulation-based TMY generation method has no geographical or climatological limits in principle, though it was validated using the Estonian humid continental climate (Dfb) with typical reference buildings. The method is described without geographical boundaries and can be applied in any region to generate specific TMYs. This geographic independence represents a major advancement over previous methods, as the new approach is not dependent on manual weighting-factor adjustment of climate parameters as in other approaches from the literature. The elimination of climate-parameter weighting-factor selection makes the method universally applicable without requiring region-specific calibration.

The efficacy may vary depending on specific regions or climatic conditions, but current discussions for TMY generation methods focus mostly on cold climates, as temperature and radiation have more equal impact in warmer climates. Regarding climate parameters, the method has no preference or bias in selection. The approach eliminates the need for climate-parameter weighting-factor determination that complicates traditional methods, as typical meteorological year generation using those methods requires choosing weighting factors that vary depending on climate and geographical area. Moreover, the work and effort required to determine such weighting factors is greater than for the methods provided in this research.

The findings suggest that 5% risk level for AHU cooling coil sizing is sufficient in most practical cases including condensing room units, providing clear, evidence-based guidance for practitioners who previously relied on conservative assumptions or case-by-case judgment. For internal heat gain modeling, the research provides practical insights that designers can immediately apply. The study shows that utilizing thermal mass can reduce cooling system size by up to 7% on average, and models with large windows and light structure need the largest cooling systems. The cooling loads obtained with EN 16798-1 profiles did not significantly differ from the average of other profiles' results.

The methods can be readily integrated into existing building design workflows. The simulation-based TMY generation method is compatible with standard building performance simulation tools, particularly IDA ICE, which is commonly used in Northern European practice. The risk-level design day guidance provides immediate application for practitioners sizing cooling systems, offering clear recommendations that balance energy efficiency with thermal comfort requirements. The comprehensive validation through long-term simulations ensures that recommendations are robust and reliable for real-world application.

5.4 Standards Development Recommendations

The research provides a strong foundation for incorporating simulation-based TMY generation methods into international standards. Standards organizations may consider adopting this approach as an alternative or replacement for existing climate-parameter-based methods. Since this can be a major shift, the writer suggests that the standard attach the acknowledgement and the determination of weighting factors that assign relative importance to different climate parameters (temperature, solar radiation, humidity, and wind) and recommend equal weighting factors for all parameters to keep the current standard untouched while opening the door for practitioners to choose weighting factors from the literature if applicable. This provides an instant improvement because the results already showed that the weighting factors proposed in earlier work [13] provide more accurate results than the current standard method. However, even with this weighting approach and regional calibration specific to Estonia's climate, the method still exhibited higher deviations compared to the proposed simulation-based method.

Based on the research findings for design day generation, concrete proposals for standards updates are needed. The comparison of standards highlighted limitations of ISO 15927-2, which introduced inconsistencies. In contrast, the ASHRAE method proved more reliable, offering consistent results across all risk levels. The research suggests that ISO 15927-2 should undergo revision and should be completed with a more restrictive approach in choosing variables and rationalize the implementation effort. Since parameters used in generating design days are not of uniform importance, practitioner-dependent selection of additional climate parameters in ISO 15927-2, combined with selecting actual day data from historical records, results in inconsistency. Further analysis is required for both standards regarding the risk level and possible elimination of it and instead, integrating thermal comfort assessment.

5.5 Summary of future study and suggestions

The research recommends a phased approach for standards implementation:

1. **Immediate updates** to ISO 15927-2 to address identified inconsistencies and practitioner-dependent parameter-selection issues.

2. **Medium-term integration** of simulation-based TMY generation methods as alternative approaches within existing standards frameworks. Estonia has already adopted the results as the country's new TMY.

3. **Design Day Generation method development** by producing hybrid design day generation methods that combine the strengths of ASHRAE and ISO approaches while eliminating their individual weaknesses. The effectiveness of risk levels remains in question, and further study is needed.

4. **Comprehensive revision** of internal heat gain modeling guidelines to reflect the reality of modern building performance and the increasing importance of internal loads in highly insulated structures.

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Abstract

New method for generating weather data for energy simulation and cooling sizing of buildings

Rapid climate change and shifting meteorological conditions under which buildings must operate demand more accurate weather data and modern methodologies to enable frequent and accessible updates, as traditional weather data generation methods are increasingly inadequate for contemporary building design. Current design practices rely heavily on outdated processing of historical meteorological data, which may not accurately reflect future climate conditions, particularly for buildings intended to operate for decades. This thesis is based on five publications, and its primary objective is to develop and validate new methods for generating Typical Meteorological Years (TMY) and assessing design day weather data to improve the quality of simulation results.

The methodology encompasses four main research approaches: (1) development of a simulation-based TMY generation method that uses building energy consumption (and its duration curve) as the primary selection criterion instead of statistical selection of climate parameters, (2) comprehensive performance analysis of risk-level-based design day sizing methods according to ISO 15927-2 and ASHRAE Fundamentals standards, (3) systematic sensitivity analysis of building design parameters affecting cooling system size, including thermal mass, internal heat gains, window configurations, and occupancy levels, and (4) supporting the development of computationally efficient improvements through solar radiation-based prediction methods for early design stage applications.

Dynamic building energy simulation using IDA ICE software is employed, utilising 37 years (1990–2021) of climate data from Estonia, representing a humid continental climate (Dfb) with no dry season, typical of Northern Europe. Four reference buildings representing typical building stock were used for method validation, including offices with different window-to-wall ratios and dwellings with different insulation levels.

The main results showed significant improvements in weather data generation accuracy and cooling system design guidelines. The simulation-based TMY generation method achieved better accuracy compared to traditional climate parameter-based approaches, obtaining consistent deviation values averaging under 1% for heating and 4% for cooling, compared to 5% for heating and 7% for cooling with the EN 15927-4 standard. The mean squared error normalised by annual energy (MSE_AE) statistical method proved optimal for cold climates.

Regarding cooling system design, the comprehensive evaluation of design day generation methods showed that ASHRAE Fundamentals provided consistent and reliable results across all risk levels, while ISO 15927-2 exhibited fundamental inconsistencies and contradictory results. Risk level optimisation studies indicate that 10% risk levels are suitable for cooling room units, while 5% risk levels are appropriate for air handling systems, ensuring sufficient thermal comfort and humidity control. Thermal comfort assessment confirmed that risk level choice significantly affected system size but had minimal impact on actual comfort outcomes.

Sensitivity analysis establishes a clear hierarchy of building design parameters affecting cooling loads, with solar gains through windows showing the highest impact, followed by internal heat gains with medium-high significance, where empirical occupancy profiles demonstrate up to 35% higher requirements compared to standard EN 16798-1 assumptions. Window-to-wall ratio changes from 25% to 58% result in 35% larger cooling systems (medium impact), and thermal mass provides medium impact with up to 20% cooling capacity reduction potential in south-facing offices. Design cooling

capacities varied in the range of 22–40 W/m^2 depending on building orientation, window configuration, and risk levels, with south-facing offices without shading requiring the highest capacities.

The novelty of this thesis lies in the development of a geographically independent TMY generation method that eliminates the need to choose climate parameter weighting factors and enables reference years to be updated directly based on building energy simulation and cooling sizing climate data generation results. Additional contributions include evidence-based guidelines for cooling system sizing risk levels and quantified impacts of building design parameters on cooling requirements. This research contributes to more accurate building performance prediction, provides practical implementation strategies for improved design workflows, and establishes a foundation for updating international standards to address climate change adaptation in building design.

Kokkuvõte
Uus meetod hoonete energiasimulatsiooni ja jahutuse dimensioneerimise kliimaandmete määramiseks

Kiired kliimamuutused ja meteoroloogiliste tingimuste muutused, milles hooned peavad töötama, nõuavad rohkem kättesaadavaid ilmaandmeid ja kaasaegset tehnoloogiat, et võimaldada sagedasi ja ligipääsetavaid uuendusi, kuna traditsioonilised ilmaandmete genereerimise meetodid on tänapäevase hoonete projekteerimise jaoks üha ebapiisavamad. Praegused projekteerimispraktikad tuginevad suuresti ajalooliste meteoroloogiliste andmete aegunud töötlemisele, mis ei pruugi täpselt kajastada tuleviku kliimatingimusi, eriti hoonete puhul, mis on mõeldud töötama aastakümneid. Väitekiri põhineb viiel publikatsioonil ning selle peamine eesmärk on välja töötada ja valideerida uusi meetodeid tüüpiliste meteoroloogiliste aastate (TMY) genereerimiseks ning projekteerimispäevade ilmaandmete hindamiseks, et suurendada simulatsiooni tulemuste kvaliteeti.

Meetodistik hõlmab nelja peamist uurimislähenemist: (1) simulatsioonipõhise TMY genereerimise meetodi väljatöötamine, mis kasutab hoone energiatarbimist (ja selle kestuskõverat) peamise valikukriteeriumina klimaparameetrite statistilise valiku asemel, (2) põhjalik riskitasemepõhiste projekteerimispäevade suuruste määramise meetodite jõudlusanalüüs vastavalt ISO 15927-2 ja ASHRAE Fundamentals standarditele, (3) süstemaatiline tundlikkuse analüüs hoonete projekteerimise parameetrite kohta, mis mõjutavad jahutussüsteemi suurust, sealhulgas soojusmaht, sisemised soojuskasumid, akende konfiguratsioonid ja kasutustasemed, ning (4) toetamine arvutusefektiivsuse paranduste arendamisele päikesekiirguspõhiste ennustusmeetodite kaudu varajase projekteerimisstaadiumite rakenduste jaoks.

Uurimuses kasutatakse dünaamilist hoone energiasimulatsiooni IDA ICE tarkvaraga, kasutades 37 aastat (1990–2021) kliimaandmeid Eestist, mis esindavad niisket mandrilist kliimat (Dfb), millel puudub kuiv aastaaeg ja mis on tüüpiline Põhja-Euroopale. Meetodite valideerimiseks kasutati nelja tüüpilist hoonefondi esindavat referentshoone, sealhulgas erinevate akende-seinte suhtega kontorhooneid ja erinevate isolatsioonitasetega elamuid.

Peamised tulemused näitasid olulisi parandusi ilmaandmete genereerimise täpsuses ja jahutussüsteemide projekteerimise juhistes. Simulatsioonipõhine TMY genereerimise meetod saavutas paremat täpsust võrreldes traditsiooniliste klimaparameetritele tuginevate lähenemistega, saavutades järjepidevaid hälbeväärtusi, mis on keskmiselt alla 1% kütmise ja 4% jahutamise puhul, võrreldes EN 15927-4 standardiga 5% kütmise ja 7% jahutamise puhul. Ruutkeskmine viga, mis on normeeritud aastase energia järgi (MSE_AE), statistiline meetod osutus optimaalseks külmade kliimade jaoks.

Jahutussüsteemide projekteerimise osas näitas projekteerimispäevade genereerimise meetodite põhjalik hindamine, et ASHRAE Fundamentals pakkus järjepidevaid ja usaldusväärseid tulemusi kõigil riskitasemetel, samas kui ISO 15927-2 näitas põhilisi vastuolusid ja vastupidiseid tulemusi. Riskitaseme optimeerimise uuringud näitavad, et 10% riskitasemed sobivad jahutusruumi üksustele, samas kui 5% riskitasemed on sobivad õhukäitlussüsteemidele, tagamaks piisava soojuskomfordi ja niiskuskontrolli. Soojuskomfordi hindamine kinnitas, et riskitaseme valik mõjutas oluliselt süsteemi suurust, kuid avaldas minimaalset mõju tegelikele komfordi tulemustele.

Tundlikkuse analüüs loob selge hierarhia hoonete projekteerimise parameetritest, mis mõjutavad jahutuskoormusi, kusjuures päikesekasumid akende kaudu näitavad kõrgeimat mõju, millele järgnevad sisemised soojuskasumid keskmiselt kõrge tähtsusega,

kus empiirilised kasutustaseme profiilid näitavad kuni 35% kõrgemaid nõudeid võrreldes standardsete EN 16798-1 eeldustega, akende-seinte suhte muutused 25%-lt 58%-le toovad kaasa 35% suuremad jahutussüsteemid (keskmine mõju), ning soojusmaht pakub keskmist mõju kuni 20% jahutuvõimsuse vähendamise potentsiaaliga lõunasuunalistes kontorites. Projekteerimise jahutuvõimsused varieerusid 22–40 W/m^2 vahemikus sõltuvalt hoone orientatsioonist, akende konfiguratsioonist ja riskitasemetest, kusjuures lõunasuunalised kontorid ilma varjutuseta nõudsid kõrgeimaid võimsusi.

Selle väitekirja uudsus seisneb geograafiliselt sõltumatu TMY genereerimise meetodi väljatöötamises, mis kõrvaldab vajaduse valida kliimaparameetrite kaalutegureid ning võimaldab referentsaastaid ajakohastada otse hoonete energiasimulatsiooni ja jahutuse dimensioneerimise kliimaandmete genereerimise tulemuste põhjal. Lisaks panused hõlmavad tõenduspõhiseid juhiseid jahutussüsteemide suuruse määramise riskitasemete jaoks ja kvantifitseeritud mõjusid hoonete projekteerimise parameetrite jahutusevajaduste osas. See uurimus aitab kaasa täpsemale hoone jõudluse ennustamisele, pakub praktilisi rakendamisstrateegiaid täiustatud projekteerimise töövoogude jaoks ja loob aluse rahvusvaheliste standardite uuendamiseks kliimamuutuste kohanemise käsitlemiseks hoonete projekteerimises.

Appendix 1

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New typical meteorological year generation method based on long-term building energy simulations

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ABSTRACT

Outdoor climate data are needed to predict building energy use. Since the 1980s, Typical meteorological Years (TMY) have been developed based on actual observed, typically 30-year-long, meteorological data. EN 15927-4 uses Finkelstein-Schafer statistics to construct a TMY. To address varying climate parameters' impact on energy use, EN 15927-4 method requires supplementary weighting factors that correlate with the climate parameters' impact. However, there is no straightforward method to select these weighting factors, and often, building performance simulations with reference buildings are conducted. To eliminate weighting factor determination uncertainty, this study proposes a TMY-generating method fully based on long-term energy simulations. As the main finding, it was shown that using building energy simulation results instead of climate parameters to determine the best months for TMY corresponded better with the average annual energy needs of the 31-year period. In principle, the developed method has no geographical/climatological limits, but it was tested with the Estonian cold and dry climate and typical reference buildings. The best statistical method for TMY generation was mean square error normalized by average annual heating/cooling need. It reflected long-term global warming and has low and consistent deviation values from 31-years results averaging less than 1 % for heating and 4 % for cooling compared to EN 15927-4 with 5 % for heating and 7 % for cooling and EN 15927-4 with weighting factors with 4 % for heating and cooling. The developed TMY generation method has wide application potential, and it can be recommended to be validated in other climates in the future.

1. Introduction

About 28 % of global energy-related greenhouse gas emissions are caused by buildings [1] and the energy performance of buildings is crucial to reduce our impact on global warming. Since energy simulation and estimating a building's energy consumption is a natural part of designing an energy-efficient building, the outdoor climate input data in simulations is essential. The dimensioning of cooling/heating systems and estimating the annual energy consumption of buildings require reliable meteorological data. Various research has been conducted to provide meteorological data for indoor climate and energy simulations. When no hourly database is available for the site, only a few forms of meteorological data may be offered, such as average days extracted from an existing database or fictional data created by a program employing several pre-established models [2]. However, hourly meteorological data is available for many places worldwide.

The development of design day data for dimensioning cooling and heating systems started in the 20th century [3]. For the precise measurement of heating and cooling systems in buildings, design day data is an essential factor. This data provides the expected maximum and minimum temperatures, humidity levels, and solar radiation for a specific location on the warmest and coldest days of the year. In the middle of the 20th century, the American society of heating, refrigerating, and air-conditioning Engineers (ASHRAE) first introduced design conditions for various U.S. locations [4]. Since then, ASHRAE [5], the International energy conservation code (IECC), and the European Committee for Standardization (CEN) have published guidelines and standards for calculating design day data for various regions in the world. For the optimal design and operation of heating and cooling systems, it is essential to calculate design day data accurately [6,7].

Many studies suggest future scenarios, validate design day calculation methods, or provide alternatives to the traditional design day

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methods. Garcia et al. evaluated the typical illuminance year generation method from long-term data [8]. Farahani et al. showed how the dimensioning results could differ with different future climate scenarios in the Finnish climate, which is similar to Estonia [9]. Pezzi et al. checked the quality and performance of the design days selection based on EN ISO 15927-2 [10,11]. Carlucci et al. reviewed many articles that used Data-driven models and machine learning-based approaches to model occupant behavior and predict the loads for system sizing [12].

The development of reference years for energy simulation modeling started in the 1980s. There were methods of generating meteorological years before that could have a different algorithm to generate typical meteorological years, but all studies and methods were based on actual observed meteorological data. The two terms, test reference year (TRY) and typical meteorological year (TMY), are both used to address the same climate data representing the climate of a region that can be used for energy simulations. During the 1990s and 2000s, many studies developed TMY or TMY generation methodologies for different regions [13].

The EN ISO 15927-4 [14] standard presents a method using Finkelstein-Schafer statistical parameters to generate a TMY from at least 10 years of meteorological data [14]. The method considers temperature, solar radiation, and humidity as the primary determining climate parameters and wind as the secondary parameter for TMY generation. The provided method is assessed by Refs. [15,16] for building simulations and designing photovoltaic systems. It has also been used in multiple studies and simulations ever since, and the representativeness of the resulting TMY was good. Still, the impact factor for different climate parameters was investigated in Refs. [17,18].

Kalamees et al. [17] investigated the impact of different climate parameters on TMY generation. They suggested that air humidity and wind speed do not have a significant role in TMY generation for Finland's cold climate while providing weighting factors for temperature and radiation for each month. This method is explained in detail in section 1.1. The weighting factors provided for the Finnish cold climate [17] differ from what Giovanni et al. provided for the Italian context [19]. Hosseini et al. used machine learning techniques to determine such weighting factors and compared five training approaches to find the most suitable weighting factors to improve energy performance estimation [20].

Drury B et al. argued that using a "typical" meteorological year may not be adequate for building performance simulations, and the uncertainty of methods for generating such a year and the found results reflect the need for using several weather files for a simulation [21]. This was also the conclusion of another study that provided a method for TMY (typical meteorological year) weather file generation using a Genetic Algorithm [22]. On the contrary, Giovanni et al. developed extreme reference years to cope with the typicality of the reference years and provided two alternatives for selecting the reference months [23]. Yuan et al. developed a calibration method to generate calibrated typical meteorological years to increase the performance of the designed systems in zero-energy buildings. They used the quantile mapping method for bias correction and, therefore, calibration, resulting in a reference year representing both extreme and typical weather information [24]. Similarly, an improved method for generating TMY is developed and presented for the Chinese climate [25].

Fan et al. employed machine learning and deep learning techniques to develop the TMYs using meteorological data, which is also concentrated on climate parameters and applied to the Chinese climate [26]. Evola et al. Li et al., and Moradi et al. compared the simulation results using a typical weather year or actual weather year in order to provide reliability factors for both system sizing and estimation of energy usage of the buildings [27,27,28]. Sun et al. employed energy simulation results for generating TMYs. However, the method is based on the typical standard method that uses climate parameters and simulation results to calibrate the generated TMY by minimizing a targeted deviation [29].

Despite the numerous methods developed for generating TRY and TMY for energy simulations, there are still identifiable issues considering these methods' accuracy, subjectivity, or time-consuming nature. Even though early methods relied on observed meteorological data, they have been found to be largely inaccurate since the impact of different climate parameters is not the same in energy simulation results. Newer methods, which consider different importance for temperature, solar radiation, humidity, and wind, necessitate subjective weighting factors for various climatic parameters, which can lead to varying results across regions and subjectivity in weighting factor selection. Moreover, the generation of TRY and TMY can be time-consuming and labor-intensive using a number of contemporary methods. Therefore, additional research is required to develop more accurate, objective, and efficient methods for TRY and TMY generation in order to enhance building performance simulations and energy efficiency studies.

This study presents a new method of TMY generation and the results compared with the most typical methods from the literature in the Estonian context. The goal was to mitigate the subjectivity of generating TMYs and to increase the speed and accuracy of energy simulation estimations by using simulation results as the base for TMY generation. This study's novelty lies in choosing the best representative months for the TMY based only on the long-term energy simulation results of the reference buildings instead of the climate parameters. This means that the historical hourly data of temperature, radiation, humidity, or other climate parameters were used to model the hourly cooling/heating need, which was then used to select the most representative month. The different weather conditions of the months within the analyzed period and the interaction of climate parameters were taken into account indirectly through their impact on the simulation results. This eliminated the inaccuracy of considering all weather parameters have the same impact according to EN ISO 15927-4 [14] or the need to identify the weight of the climate parameters [17], which can be a subjective process and requires a more considerable amount of reference building simulations compared to the approach presented in this study.

Several statistical methods were used to identify the most representative months during the process. The method for TMY generation based on simulation results is described without geographical boundaries. It can, in principle, be applied in any region to generate a specific TMY. However, the weather data and the reference buildings used in this study were typical for the Estonian cold and dry climate. For every other region, it is necessary to consider the local construction traditions and choose representative reference buildings. Additionally, the simulations should be conducted so that all climate parameters with significant influence are considered correctly.

2. Methods

This study provides a new method for generating TMY, as detailed in 2.2. To evaluate the proposed method, two other methods detailed in 2.1 are used for comparison. To briefly describe an overview of all methods, they are summarized as follows:

1. EN ISO 15927-4 method:
   - Applies the standard method without climate parameter weighting factors [14].
   - Utilizes climate parameters (temperature, radiation, humidity, wind) on an hourly basis.
2. EN ISO 15927-4 method with weighting factors:
   - Utilizes the standard method with added climate parameter weighting factors, proposed by Kalamees et al. [17].
   - Utilizes climate parameters (temperature, radiation, humidity, wind) on an hourly basis.
3. Proposed simulation-based TMY generation method:
   - Utilizes cooling/heating needs from long-term simulations of reference buildings instead of climate parameters.
   - Cooling/heating needs are derived from hourly long-term simulation results.

A summary graph of the three main methods discussed in this paper is illustrated in Fig. 1.

The methodology of all approaches requires historical weather data collection, including hourly temperature, radiation, humidification, wind speed, and direction. To minimize the description of the methods, the methods are described in detail, including case study input, to avoid double information. The case study is to define TMY for the Tartu region, Estonia. Firstly, historical weather data was obtained from a weather station in the Tartu region, Estonia, from 1990 to 2020. For method 3, proposed in this study, reference buildings are needed. Four reference buildings representing building stock in Estonia were chosen and described under section 2.3. For method 2, weighting factors for the region Estonia are needed, presented in Ref. [17] and equation (5) under section 2.2. In this section, a detailed description of how to implement methods 1,2 and 3 are presented under sections 2.1 and 2.2, the reference buildings are illustrated under section 2.3, and the approach for presenting the results for TMY comparison is mentioned under section 2.4.

It is important to mention that the current TMY for Estonia that practitioners currently use is based on historical data from 1970 to 2000 and developed using method 1. This is also included for result presentations to reflect the global warming effect and the necessity for updating Estonian TMY.

2.1. Climate parameter-based method for TMY generation

The method presented by Kalamees et al. [17] is an adjusted version of the EN ISO 15927-4 [14] method. Consequently, both methods are discussed concurrently in this section. The adjustment involves assigning varying significance to different climate parameters each month. For instance, outdoor temperature plays a more crucial role in determining energy usage during winter months in northern Europe; therefore, it has a higher significance. These variations in importance are quantified using weighting factors that are elaborated in this section. The description covers both methods simultaneously, with a division in the middle to highlight the differences.

The following procedure was derived from EN ISO 15927-4, which should be followed for every climate parameter _p_ (temperature, solar radiation, and humidity):

a) Calculate the daily means of each climate parameter, p

b) For each calendar month (MM/all years), calculate the Cumulative Distribution Function (CDF) of the daily means over all years. For CDF calculation, the daily mean values should be sorted in increasing order and ranked, and the rank is divided by the total number of values.

$$\Phi(p, m, i) = \frac{K(i)}{N + 1} \tag{1}$$

Where $K(i)$ is the rank order of the ith value of the daily means within that calendar month (m) in the whole dataset, and N is the total number of data points for that month in the whole dataset.

c) Sort all the values for that month and that year in ascending order, and then use equation (2) to get the cumulative distribution function, F (p,y,m,i), of the daily means within each calendar month for each year of the data set:

$$F(p, y, m, i) = \frac{J(i)}{N + 1} \tag{2}$$

Where $J(i)$ is the rank order of the ith value of the daily means within that month (m) and that year (y).

d) For each calendar month and each year, add the Finkelstein-Schafer (F.S.) value of the climate parameters using equation (3) according to EN ISO 15297-4 [14] and equation (4) according to Kalamees et al. [17]) and rank the result.

$$F.S_{(y,m)\ total} = \sum_{p=1}^{n} F.S_{(p,y,m)} \tag{3}$$

$$F.S_{(y,m)\ total} = Wp \times \sum_{p=1}^{n} F.S_{(p,y,m)} \tag{4}$$

where Wp is the weighting factor for the corresponding climate parameter.

e) For each calendar month, for the three months with the lowest total ranking, calculate the deviation of the monthly mean wind speed from the corresponding multi-year calendar month mean. The month with the lowest deviation in wind speed is the selected month.

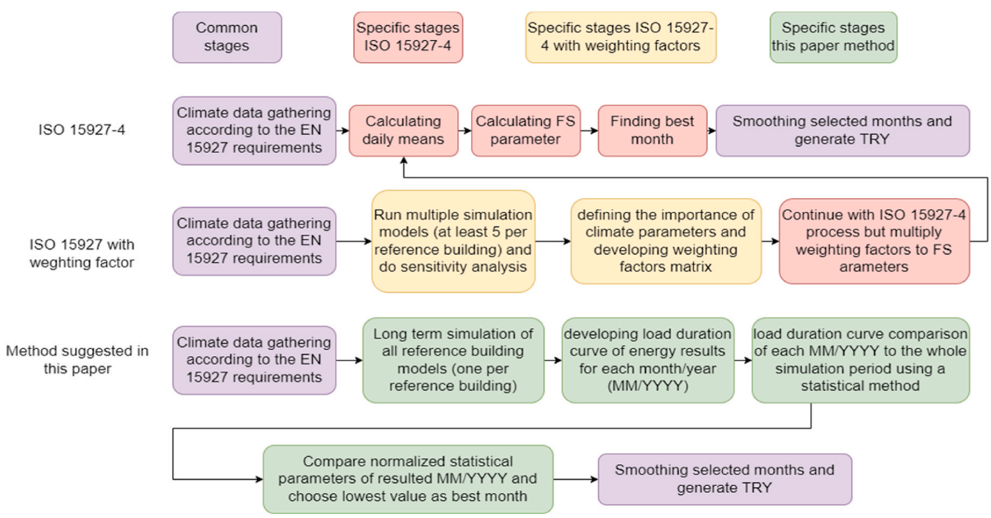

Fig. 1. Summary of processes needed for generating TMY based on EN ISO 15927-4 [14], adjusted ISO 15927-4 [17] and the method suggested in this paper.

The calculated F.S. of all parameters should be summed up after multiplying the weighing factors. ($w_{(p,m)}$) the first line is of the weighting factors matrix is for temperature and the second line is for radiation. According to Kalamees et al. [17], humidity weighting factor is 0 for all months and can be omitted.

$$F.S_{(y,m)\ total} = \sum_{p=1}^{n} \left(w_{(P,m)} \times F.S_{(P,y,m)} \right) \quad (5)$$

$$w_{(p,m)} = \begin{pmatrix} Jan & Feb & Mar & Apr & May & June & July & Aug & Sep & Oct & Nov & Dec \\ 1 & 1 & 0.8 & 0.8 & 0.5 & 0.5 & 0.5 & 0.5 & 0.8 & 0.8 & 1 & 1 \\ 1 & 1 & 0.2 & 0.2 & 0.5 & 0.5 & 0.5 & 0.5 & 0.2 & 0.2 & 1 & 1 \end{pmatrix}$$

$$F.S_{(y,m)\ total} = w_{(Temp.)} \times FS_{(Temp.)} + w_{(Rad.)} \times FS_{(Rad.)} + 0 \times FS_{(Hum.)}. \quad (6)$$

To ensure a seamless transition when the "best" months are combined to make the TMY, the parameters in the final 8 h of each month and the beginning 8 h of the following month shall be determined using interpolation. The last 8 h of December and the first 8 h of January should be included in this modification so that the reference year may be used repeatedly in simulations.

2.2. Hourly simulation-based method for TMY generation

This new method aims to create a Typical Meteorological Year, which, after being used in simulations, results in hourly cooling/heating needs with the closest possible load distribution function curve to the cooling/heating needs resulting from long-term simulations using meteorological data. The proposed method uses long-term simulation results for the assessment instead of actual climate parameters. The process chooses one month among all available months and concatenates 12 selected months to create the TMY.

The data preparation, concatenation, and smoothing for finalizing the TMY are the same as defined for other methods under 2.1. This method needs to use reference buildings with occupancy and operation patterns, solar gains, and heat losses, which will describe a wide variety of the building stock. In this study, both non-residential and residential buildings are used. Reference buildings were modified to have a different share of heat losses through the building envelope and solar radiation in the annual energy balance of reference buildings. This was achieved for the office building by changing the window-to-wall ratio by a factor of 2 and for the residential building by modifying the thermal transmittance of the building envelope to represent an old and a new building.

2.2.1. Method's implementation workflow

The workflow of the long-term hourly simulation-based method is summarized in points below:

1. Gather hourly heating and cooling needs from a 31-year simulation using IDA ICE 4.8 [30] software for each reference building (4 reference buildings are used.)
2. A statistical method, as detailed in 2.2.2, shall be used to find the most representative months for TMY generation for each reference building. The most representative month is the month with the closest cooling/heating needs distribution curve.
3. If necessary, add normalization to the statistical formula.
4. Compare the resulting values from the formula and choose the month with the lowest statistical deviation from the long-term simulation results.
5. Find the minimum value between four cases and report that month for the final TMY.
6. Generate TMY using selected 12 months.

Smoothing, according to EN 15927-4 [14], should be implemented before combining months and creating the final TMY.

2.2.2. Finding the most representative month using statistical formulas

To find each month of the TMY, the load duration curve of each month was compared to the load duration curve of that month during the whole 31 years. (For example, the curve of January 1990 compared to the curve of all January months combined from 1990 to 2020). The energy needs of space and ventilation heating and cooling were included, and the heating and cooling needs had positive and negative values, respectively. This allowed the production of a single duration curve for each month as heating and cooling occurred most of the months for all reference buildings.

Several statistical methods for measuring deviation were employed to implement such a comparison, listed in Table 1. Different methods were chosen to measure each method's accuracy and find the method with the least deviation in energy simulation results. For this comparison, every data point in the month is compared to the corresponding data point in 31-year results using one of the equations in Table 1, wherein all formulas, y_i and $\hat{y}_i$ are the heating/cooling needs of each data point for a month and the corresponding 31-year load duration curve data point, respectively, and n is the total number of available data points (in hourly climate data, n for each month equals 31 × 24).

To be able to compare the deviation of the statistical methods for all reference buildings without considering their occupancy area, the final formulas are normalized. Two normalization values were used in the process. The first one is the range of the variables in the dataset, which is equal to the difference between maximum and minimum values in the dataset (maximum heating capacity (positive value) - maximum cooling capacity (negative value)). The second normalization factor is the total annual energy used in the buildings. The formulas after normalization are presented in Table 1. $TE(b_j)$ is the total annual energy use of each building type.

2.3. Selected building models for case study TMY generation, Estonia

Four building simulation models were selected as reference buildings. We chose an office building model and a single-family detached house to capture the differences in usage and operation profiles of non-residential and residential buildings. These two models were adjusted to have a reference building stock with varying proportions of solar heat gains in the heat balance of the buildings. The reference buildings used are as follows:

Table 1
Statistical methods employed to generate TMYs in this study. (normalization factors are shown in red).

Method	Formula	
Mean Absolute Error, Normalized by **annual energy (MAE_AE)**	$MAE(y,\hat{y}) = \frac{1}{n} \left(\sum_{i=0}^{n-1} \lvert y_i - \hat{y}_i \rvert \right) / TE(b_j)$	(7)
Mean Absolute Error, Normalized by **dataset range (MAE_DR)**	$MAE(y,\hat{y}) = \frac{1}{n} \sum_{i=0}^{n-1} \frac{\lvert y_i - \hat{y}_i \rvert}{\max(y_i) - \min(y_i)}$	(8)
Mean Squared Error, Normalized by **annual energy (MSE_AE)**	$MSE(y,\hat{y}) = \frac{1}{n} \sum_{i=0}^{n-1} \left(\frac{y_i - \hat{y}_i}{TE(b_j)} \right)^2$	(9)
Mean Squared Error, Normalized by **dataset range (MSE_DR)**	$MSE(y,\hat{y}) = \frac{1}{n} \sum_{i=0}^{n-1} \left(\frac{y_i - \hat{y}_i}{\max(y_i) - \min(y_i)} \right)^2$	(10)
Root Mean Squared Error, Normalized by **dataset range (RMSE_DR)**	$RMSE(y,\hat{y}) = \sqrt{\frac{1}{n} \sum_{i=0}^{n-1} \left(\frac{y_i - \hat{y}_i}{\max(y_i) - \min(y_i)} \right)^2}$	(11)
Coefficient of determination, **R_Squared**	$R^2(y,\hat{y}) = 1 - \frac{\sum_{i=0}^{n-1} (y_i - \hat{y}_i)^2}{\sum_{i=0}^{n-1} (y_i - \bar{y}_i)^2}$ Where $\bar{y} = \frac{1}{n} \sum_{i=0}^{n-1} y_i$	(12)
Finkelstein Schafer method, used in ISO 15927-4	The following steps are mentioned under section 1.1, but hourly cooling/heating energy needs resulting from simulations instead of a climate parameter.	

- Office building with small windows.
- Office building with big windows.
- Single-family house representing new building with highly insulated envelope.
- Single-family house representing old building with poorly insulated envelope.

For office buildings, the small window sizes are half the big windows to consider the influence of the solar heat gains on the heat balance. The windows in the old house have doubled thermal transmittance to represent an old house. By covering a variation of cooling/heating needs using these four reference buildings, it was assumed that four reference buildings are sufficient for the purposes of this study. For application of the TMY generation method in other locations and climates, the selection of reference buildings should correspond with the local building customs and consider the potential variation in the energy needs of buildings. E.g., in humid climates, the building parameters affecting the energy needs for dehumidification should be considered. However, in this study, these considerations were omitted because outdoor relative humidity was not an essential parameter for the energy needs of typical buildings.

The building models used in this study are slightly adjusted versions of building models used in cost optimality study in Estonia [31]. The 3D model of the buildings are shown in Fig. 2. The usage profiles for internal heat gains are according to EN 16798-1 [32] open plan office and detached residential house. Specifications of the reference buildings and the parameters that are used in the simulations are presented in Table 2, Table 3, and Table 4. The solar heat gain coefficient of glazed areas was 0.5 for houses and 0.3 for office buildings.

Table 2
Parameters used in the simulations of the reference buildings.

Parameter	Unit	Office building	Single-family House
Gross area	m^2	4958	100
Number of stories		6	1
Number of zones		42	12
WWR,	%	60 % & 30 %	17 %
Occupants,	person/ m^2	0.0586 (open office profile)	0.532
Equipment,	W/m^2	12	2.4
Lighting,	W/m^2	12	8
Ventilation airflow rate	$L/(s{\cdot}m^2)$	2	0.42
Infiltration constant air flow rate	$L/(s{\cdot}m^2)$	0.056	0.0238
Temperature set points, heating/cooling		21/25	21/25

2.4. TMY illustration approach for comparison

For the illustration of different TMY data resulting from all methods mentioned in the previous sections, cooling degree hours and heating degree days are calculated for the temperature of TMYs [33], and the comparison is presented in the results section. The TMY data was then used to simulate case study buildings, and the annual energy needs were compared. A chart of temperature and radiation, together with a graph showing the temperature and radiation load duration curves of all TMYs, is also presented.

2.4.1. Cooling degree hours

According to Estonian regulation [33], The risk of overheating shall be calculated for a "critical room." Since ideal coolers are used to suggest the best TMY, the method used the dry-bulb temperature of the TMYs to calculate the number of hours with the high demand for cooling during

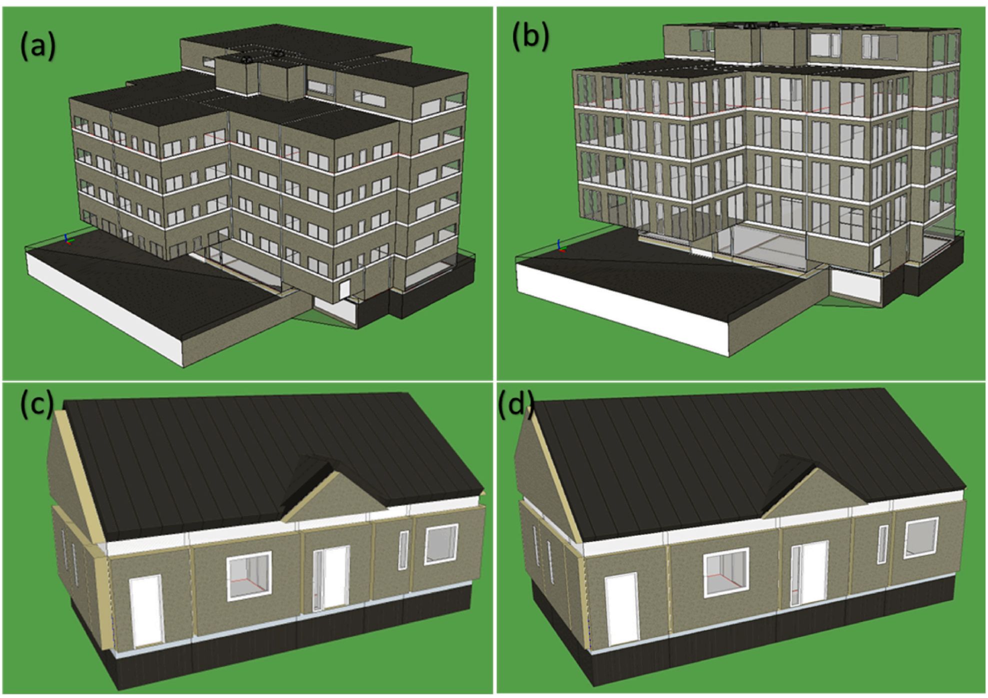

Fig. 2. 3D Model of the reference buildings. (a) office building with small windows, (b) office building with big windows, (c) single-family house with thick walls (lower U value, representing new house), and (d) single-family house with thin walls (representing old house).

Table 3
Building specifications, single-family house.

Structure	Area	Old single-family house		newly built single-family house	
	Area, m^2	Thermal transmittance, U	Specific heat loss, H	Thermal transmittance, U	Specific heat loss, H
		W/(m^2.K)	W/K	W/(m^2.K)	W/K
Roof	130	0.2	26	0.1	13
Slab on ground	100	0.24	24	0.12	12
External wall	138	0.26	35.88	0.12	16.56
Doors	5.9	2.2	12.98	2.2	12.98
Windows	10.2	1.8	18.41	0.9	9.21
Specific heat loss for heated area H/A, W/(m^2·K)		1.33		0.81	
Total specific thermal transmittance U.A [W/K]		133.30		81.43	

Table 4
Building specifications, office.

Structure	Thermal transmittance,	Specific heat loss H,	Office, big windows	Office, small windows
	W/(m^2.K)	W/K	Area, m^2	Area, m^2
Roof	0.16	178.9	1118	1118
External floor above air	0.82	136.9	167	167
Slab on ground	0.82	893.8	1090	1090
Internal Slab, b/w garage and 1st floor	0.45	289.8	644	644
External wall	0.3	334.4	1115	1775
External wall basement	0.3	73.5	245	245
Doors	1.8	27	15	15
Windows	0.6	791.4	1319	660
Specific heat loss for heated area H/A, W/(m^2·K)			0.38	0.32
Total specific thermal transmittance, U.A [W/K]			1871	1578

summer. According to the methodology, the formula for calculating degree hours is as follows:

$$DH_{tb} = \sum_{j=1}^{j} (t_i - t_b)^+ \tag{13}$$

where DH_{tb} is the temperature excess in degree-hours compared to the base temperature t_b (°C), t_i is the hourly mean outdoor, and j is the total number of hours with a temperature higher than the base temperature during the given period. The cooling degree hours are assumed to be from the 1st of April to the 30th of September. The degree hours base temperatures are 25 °C for residential buildings and 27 °C for non-residential buildings, and the calculation should include only occupied hours (24 h/7 days for residential and from 07.00 to 18.00/5 days for offices).

2.4.2. *Heating degree days*

Heating degree day compares a location's mean outdoor temperature to a base temperature. Extreme temperatures increase degree days. The formula for calculating degree days is as follows:

$$HDD_d = -\sum_{j=1}^{j} (t_i - t_b)^- \tag{14}$$

where HDD_d (°C) is the temperature difference, t_b (°C) is the base temperature, t_i (°C) is the daily mean outdoor temperature, and j is the total number of days with a mean temperature lower than the base temperature during the given period. Typically, the degree days base temperature of 13 °C is used for old and well-insulated residential buildings and 17 °C for office buildings.

3. Results

The results section is divided into three parts: climate parameter-based method results, simulation-based method results, and a comparison between them. The first part indicates the selected months using methods 1 and 2, with a detailed presentation of weighted month/year combinations. The second part contains an analysis for choosing the most suitable statistical formula for the implementation of method 3, and a brief comparison is provided in the last section.

3.1. *Climate parameter-based TMYs*

Methods 1 and 2, presented in the methods section, are used for evaluation purposes. The selected months from method 1 are based on having the same weighting factor for temperature, radiation, and humidity, while the second method excludes humidity by providing a weighting factor of 0 for the cold and dry climate of Estonia for all months.

The selected months based on method 1 are listed in Table 5.

In Table 1 in appendix all possible selection groups based on different weighting factors for temperature (the radiation weighting factor is the complement of the temperature weighting factor, and the sum of the two shall always be equal to 1) is presented to facilitate a more detailed comparison between the methods. It's of importance to mention that with any weighting factor range, the months selected with this paper's method will never be selected. In contrast, the range of weighting factors cannot impact as much as the sensitivity analysis results concluded in Refs. [17,19].

3.2. *Hourly simulation-based TMY*

This section presents the results of the proposed method of this study. The results of the building's annual energy needs that are necessary to perform the normalization described in the proposed method are shown in Fig. 3.

3.2.1. *Deviation analysis*

This analysis is for assessing the numerical difference between the methods and the average result of the 31-year simulations. These differences are calculated and listed in Table 6 while the cooling/heating needs values are presented in Fig. 4 and Fig. 5.

The trendline resulting from linear regression over the heating/cooling needs from a 31-year simulation of reference buildings is a dotted line in the charts. From this comparison, the bold outcome is the current Estonian Typical meteorological year results, which are based on climate data from 1970 to 2000. It results in about 30 % lower cooling needs. This can relate to the fact that the average temperature in Estonia has risen due to global warming. The Finkenstein-Schaefer statistical method for finding the closest line did not perform well when only one variable (simulation results) was evaluated. This can be due to the nature of the method, which is more suitable for finding the closest line in a multi-variable problem. On the contrary, the RMSE_DR, MSE_AE, and MAE_AE resulted in lower deviation values within a short range compared to other methods.

The ISO method based on 1990–2020 data underestimated the heating and cooling needs by 4–6 % and 1–13 %, respectively. Using the climate parameter weighting factors slightly decreased the deviations from long-term simulation results. As mentioned in the previous section,

Table 5
Selected month/year using EN ISO 15927-4 method.

Month	1	2	3	4	5	6	7	8	9	10	11	12
Year	1999	2017	2016	2012	2011	2016	2013	2011	1998	1999	2019	1990

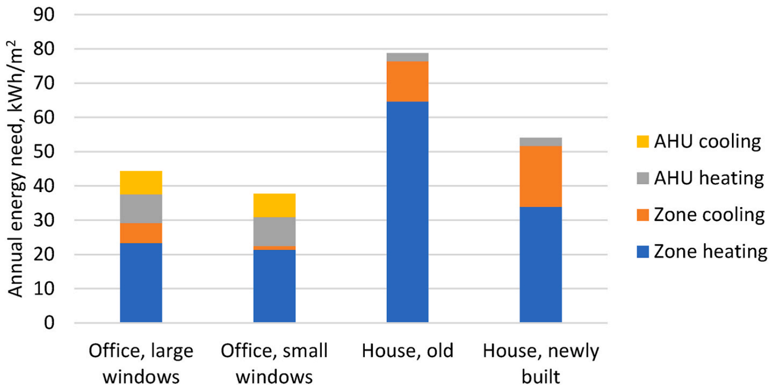

Fig. 3. The annual heating and cooling needs for each building type used for normalization formulas.

Table 6
The deviation value of simulation results based on generated TMYs compared to the average of 31-year simulations.

Building		ISO 70 - 2000		ISO 90 - 2020 + weighting factors		MSE_DR		MAE_AE	
		Zone heating	Zone cooling	Zone heating	Zone cooling	Zone heating	Zone cooling	Zone heating	Zone cooling
Office Building	Big windows	-2%	-25%	-5%	0%	-2%	9%	-3%	-3%
	Small windows	-2%	-32%	-5%	-5%	-2%	5%	-4%	-2%
House	Old	5%	-35%	-3%	-7%	-1%	8%	-1%	-4%
	New	4%	-24%	-3%	-4%	0%	9%	-2%	-5%
Building		MSE_AE		RMSE_DR		ISO 90 - 2020		Finkelstein Schafer	
		Zone heating	Zone cooling	Zone heating	Zone cooling	Zone heating	Zone cooling	Zone heating	Zone cooling
Office Building	Big windows	1%	6%	1%	-1%	-6%	-1%	-8%	-2%
	Small windows	0%	4%	0%	-9%	-6%	-4%	-9%	0%
House	Old	-1%	4%	-1%	10%	-4%	-13%	-3%	4%
	New	-1%	3%	-1%	7%	-5%	-9%	-5%	0%

in the deviation analysis, MSE_AE, MAE_AE, and RMSE_DR performed well, whereas the two latter had heating need deviations not higher than 1 % for all reference buildings. However, RMSE_DR had cooling need deviations from −9 to 10 %, but the values with MSE_AE were consistent, ranging between 3 and 6 %. Global warming continuously reduces the energy demand during winter and increases the energy demand during summer. In the Estonian context, MSE_AE provides higher values in the cooling period and similar, or a bit lower, figures during winter. Moreover, the deviation figures are more consistent between different reference building cases than the RMSE method. Therefore, MSE_AE is the best candidate for the TMY generation method from deviation analysis.

As seen from Table 7, The MSE_AE selected some months with a poor rank when months are sorted using the ISO 15927-4 method; specifically, it is transition months with heating and cooling needs which can reflect the complexity of finding the most suitable month for TMY during these periods.

3.2.2. *Selected months for the typical meteorological year*

The climate data generated using all methods resulting in month/year are presented in Table 7. In order to find the best statistical method for generating TMY, several statistical methods are used during the implementation of method 3. The ranking of each month/year combination according to EN ISO 15927 [14] is written in parentheses. As can be seen, some statistical formulas resulted in very high ranks, especially in transition months when both cooling and heating are needed.

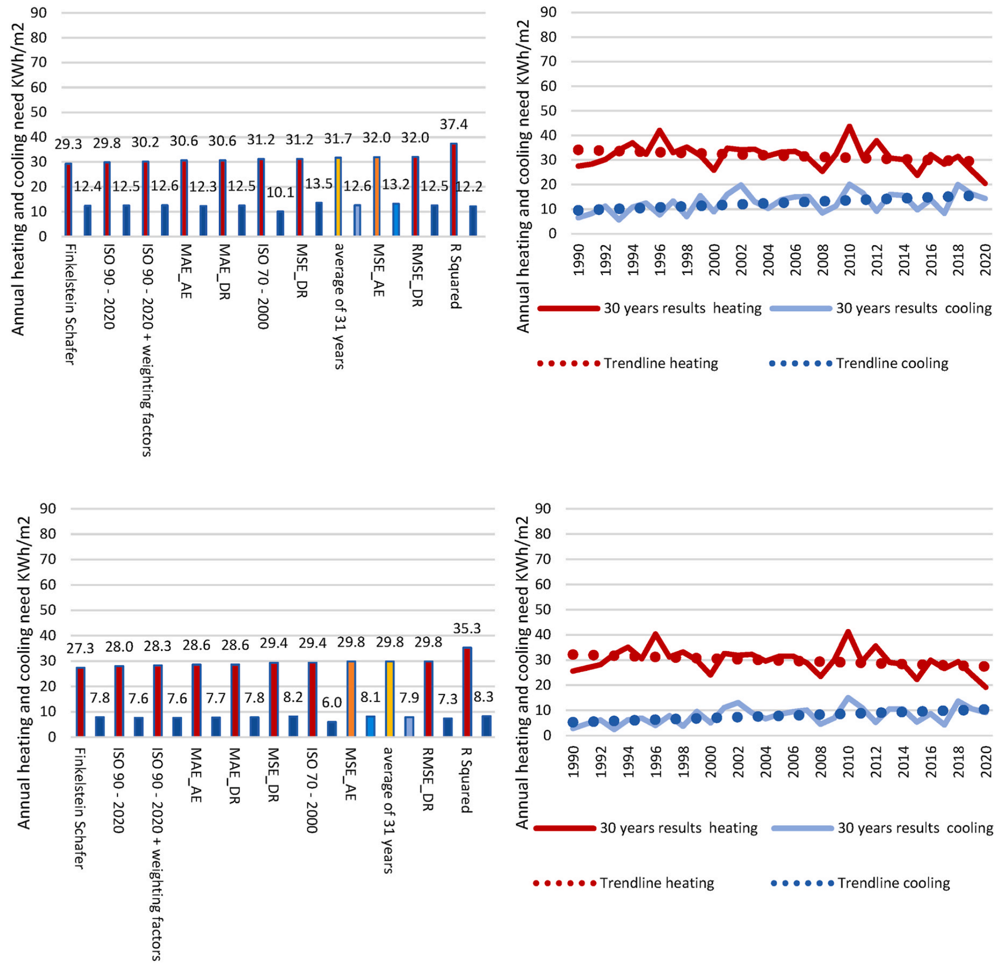

Fig. 4. Office building annual heating and cooling needs in detail. Office with large windows (upper charts) and office with smaller windows (lower charts).

3.2.3. TMY results illustration and control

As a representative, the load duration curve of the simulation results for several methods applied to the newly built single-family house model is shown in Fig. 6. The cooling/heating needs curves resulting from TMYs are qualitatively close to the 31-year curve. This qualitative check is important to ensure the process is implemented correctly and the results are relevant.

Other charts for controlling the resulted TMYs are cooling degree hours and heating degree days. In order to compare to what extent the cold and hot situations that have happened in 31-year climate files are internalized in every TMY method, the cooling degree hours and heating degree days are shown in Fig. 7.

From Fig. 7, it can be seen that the energy simulation-based method, MSE_AE, which is concluded as the best method from the deviation analysis section, has the closest heating degree days and cooling degree hours values to the average of 31 years of simulation.

3.3. Comparison between TMYs

Among the statistical methods for finding the best months, MSE_AE showed better performance in all aspects. As it is shown in Table 6, vastly used Estonian TMY that is created based on data from 1970 to 2000 and the ISO standard compared to the MSE_AE TMY has drastically lower cooling need during summer. This is aligned with the effects of global warming and is justifiable. Moreover, the energy needs deviation comparison is also presented in Fig. 8, which shows that the method suggested in this paper has lower deviations than traditional methods.

Temperature and direct normal radiation for selected TMYs are also shown in Figs. 9 and 10. Comparing the monthly average values, the climate data does not differ significantly between different options. But in a more detailed view, specifically in transition months, the differences are drastic.

4. Discussion

When choosing the method for generating TMYs, the subjectivity and applicability of the potential candidates should be assessed. The strengths and weaknesses of the new method compared to other methods are listed as follows:

Strengths:

- **Accuracy**: Compared to alternative methods, the long-term simulation method is fairly recognized for its superior accuracy in producing typical meteorological year (TMY) data. The system

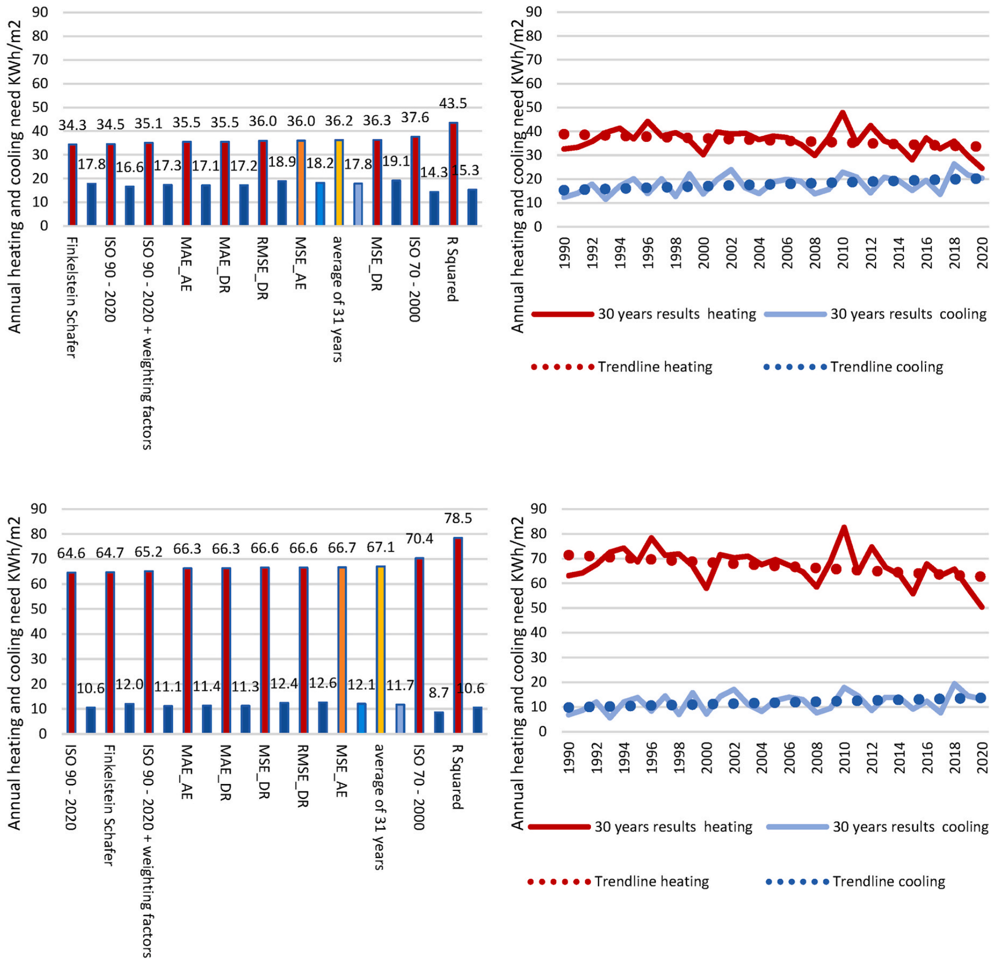

Fig. 5. Single-family house building annual heating and cooling needs in detail. Newly built houses (upper charts) and old houses (lower charts).

Table 7
Selected months using different statistical methods (YYYY(rank), ISO-based methods do not have wind criterion).

Month	ISO 15927-4	ISO 15927-4 with weighting factor	MAE_AE	MAE_DR	MSE_AE	MSE_DR	RMSE_DR	R Squared	Finkelstein Schafer
Jan	1999(2)	1999(2)	2017(5)	2017(5)	1999(2)	2017(5)	1999(2)	2003(8)	2000(4)
Feb	2017(3)	2017(3)	1998(6)	1998(6)	1998(6)	1998(6)	1998(6)	1990(11)	2017(3)
Mar	2016(1)	2016(1)	2004(3)	2004(3)	2004(3)	1998(11)	2004(3)	2005(12)	2004(3)
Apr	2012(2)	2006(3)	2007(4)	2007(4)	2018(12)	2012(5)	2018(12)	2000(14)	2007(4)
May	2011(3)	2011(3)	2003(10)	2003(10)	2009(7)	1992(6)	2011(3)	1991(12)	2003(10)
Jun	2005(1)	2005(1)	2005(1)	2005(1)	2005(1)	2005(1)	1997(10)	1993(12)	1997(10)
Jul	2013(2)	2013(2)	2012(3)	2012(3)	2012(3)	2012(3)	1997(7)	2001(11)	2012(3)
Aug	2011(3)	2011(3)	1991(4)	2001(5)	2013(6)	1991(4)	2001(5)	1998(11)	1991(4)
Sep	1998(2)	2003(3)	2012(8)	2012(8)	1995(4)	1997(11)	2012(8)	1993(12)	2012(8)
Oct	1999(3)	1999(3)	2014(4)	2014(4)	2014(4)	2014(4)	2014(4)	2002(11)	2014(4)
Nov	2014(1)	2014(1)	2014(1)	2014(1)	2014(1)	2014(1)	2014(1)	1993(11)	2003(6)
Dec	1990(2)	2014(3)	1994(5)	1994(5)	1994(5)	1994(5)	1994(5)	2006(12)	1994(5)

consistently demonstrates lower average deviations in heating and cooling, enhancing its reliability for energy simulations. Specifically, it achieved an average deviation of 5 % less than the EN ISO 15927 [14] method and 3 % less than the adjusted EN ISO 15927 [17] method.

- **Subjectivity reduction**: An advantageous aspect of this approach lies in its capacity to mitigate subjectivity during the generation of typical meteorological year (TMY) data. This is accomplished by utilizing statistical tools directly applied to energy simulation outcomes, thereby preventing the necessity for subjective weighting factors.

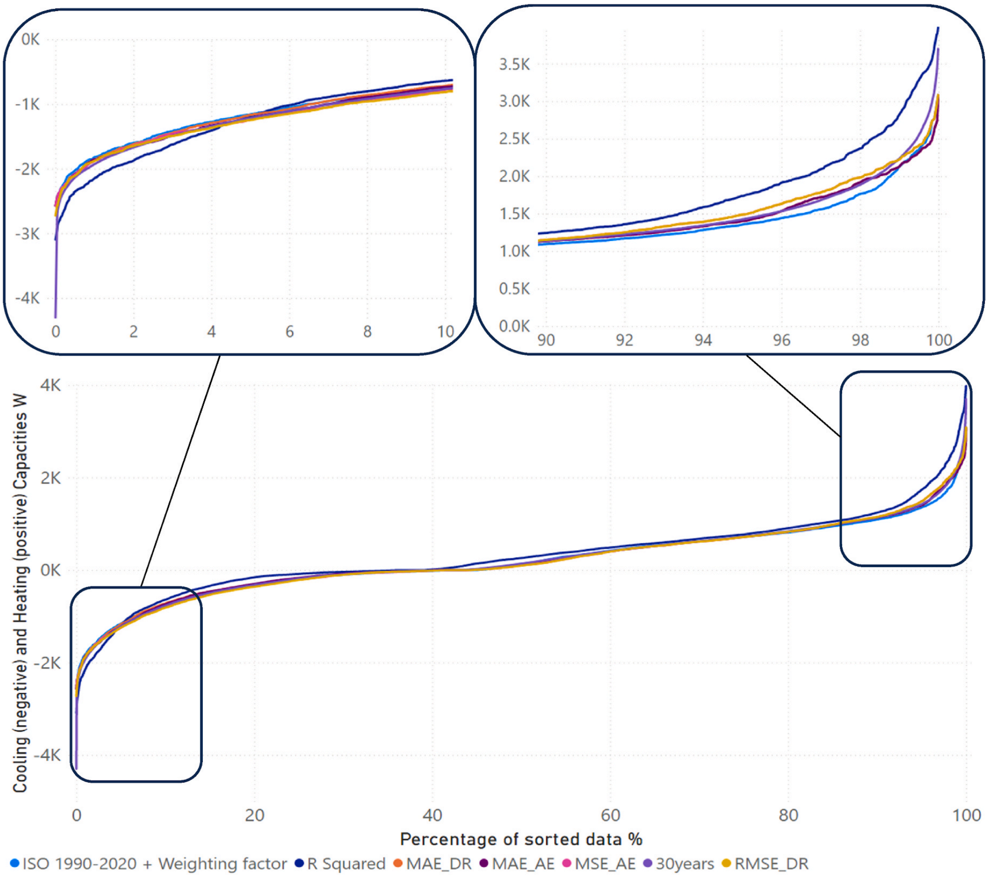

Fig. 6. Cumulative Distribution Curve of the newly built single-family houses' resulting cooling/heating capacities for selected methods from simulations using different typical meteorological years/climate files.

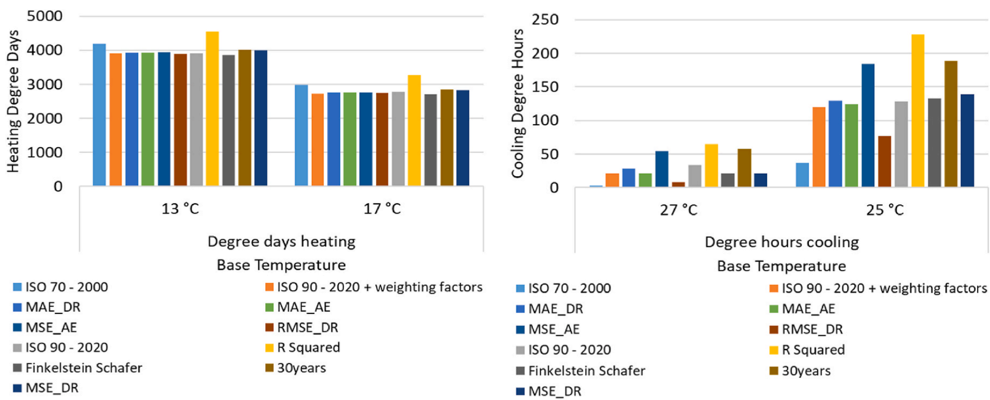

Fig. 7. Heating Degree Days (HDD) and Cooling Degree Hours (D.H.) for TMYs together with other climate data.

- **Adaptability**: The approach demonstrates the capacity to adjust to evolving climate. The ability to indirectly incorporate the impact of climate parameters and the increasing energy efficiency of buildings over time is a notable benefit for long-term planning. A few climate parameters included in the TMYs have little to no impact on the generation of TMYs in methods that are based on statistical analysis of weather parameters. However, the simulation-based method indirectly accounts for all climate parameters.

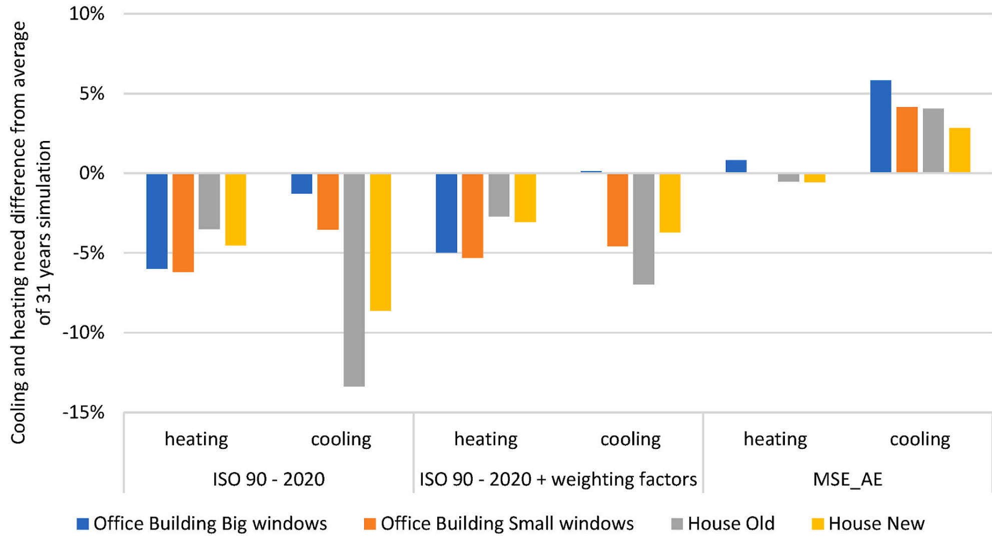

Fig. 8. Energy needs deviation comparison between the ISO 15927-4 method, adjusted ISO 15927-4 method and the suggested method in this paper.

- **Consistency**: The method employed in this study demonstrates consistent deviation estimates across different reference building scenarios, suggesting its reliability and robustness.
- **Complexity**: Although not explicitly mentioned in the text, it can be inferred that the utilization and interpretation of statistical methods directly applied to energy simulation outcomes may entail a lower level of complexity compared to other approaches that depend on climate parameters and weighting factors since statistical methods are well known, and many tools and libraries are already developed for their utilization.
- **Speed**: This newly introduced method offers a notable advantage in terms of speed. Long-term simulations with reference buildings are required only once for developing adequate TMYs. Since the current EN ISO 15927 [14] method shows inaccurate results, providing TMY using different methods from the literature needs time-consuming reference building model generation and historical weather data pre-processing. Considering this, preparing and post-processing the energy simulation results and TMY generation process can be automated; therefore the method is relatively fast.

Weaknesses:

- **Computational intensity**: The long-term simulation approach is expected to possess higher computational intensity than the original EN ISO 15927 [14] method due to its requirement for simulations spanning a prolonged duration (specifically, 31 years) and potentially involving more extensive data processing. However, since the EN ISO 15927 [14] method already shows less accurate results in this study, the suggested method should be compared with other methods in the literature, which all require even more computation effort.
- **Reference building requirement**: The acquisition of local building practices and solutions that align with the majority of the building stock is necessary for this study. However, such data and solutions may be limited in certain regions or contexts, potentially posing a constraint.
- **Limited generalizability**: The efficacy of this approach may exhibit variability contingent upon the specific region or climatic conditions, thereby constraining its applicability to broader geographical contexts. However, the current discussions for TMY generation methods are mostly for cold climates, as temperature and radiation have more equal impact in warmer climates.

The traditional methods consider climate parameters and TMY to find the best month, comparing the main climate parameters in a climate file. The main issue arises when it has been proved that not all parameters have the same impact on simulation results and cooling/heating system sizing [17]. Using weighting factors increases the accuracy of the Typical meteorological year, but choosing weighting factors is subjective and also varies depending on the climate and the geographical area of the study. Moreover, the amount of work and effort for generating such weighting factors is more compared to the methods provided in this paper. Regarding climate parameters, this paper's methods have no preference or bias in selection.

As shown in Fig. 8, the EN ISO 15927-4 [14] method did not perform well compared to the other methods, and the other methods require energy calculations with reference buildings, which can be subjective. However, the adjusted EN ISO 15927-4 [17] requires additional simulations compared to the method provided here since the sensitivity analysis shall be performed for every climate parameter to indicate if the humidity is important in the studied climate and how important the temperature is compared to the radiation. Some can argue that weighting factors should only be developed once for any region, but the weighting factors should be able to evolve in response to the improvements in the energy efficiency of buildings and alterations in climate. This paper demonstrates that long-term energy calculations with up-to-date weather data and building solutions that correspond to current practice can partially account for the varying importance of climate parameters indirectly.

5. Conclusions

In this study, we developed a new method for Typical meteorological year generation and compared it to others from the literature. The new simulation-based method suggested in this paper performs better than the conventional method provided in EN ISO 15927-4 [14]. It minimizes subjectivity and avoids using weighting factors in TMY generation compared to other fast or accurate methods. This has been done by directly employing statistical tools on energy simulation results to determine the best months rather than using climate parameters

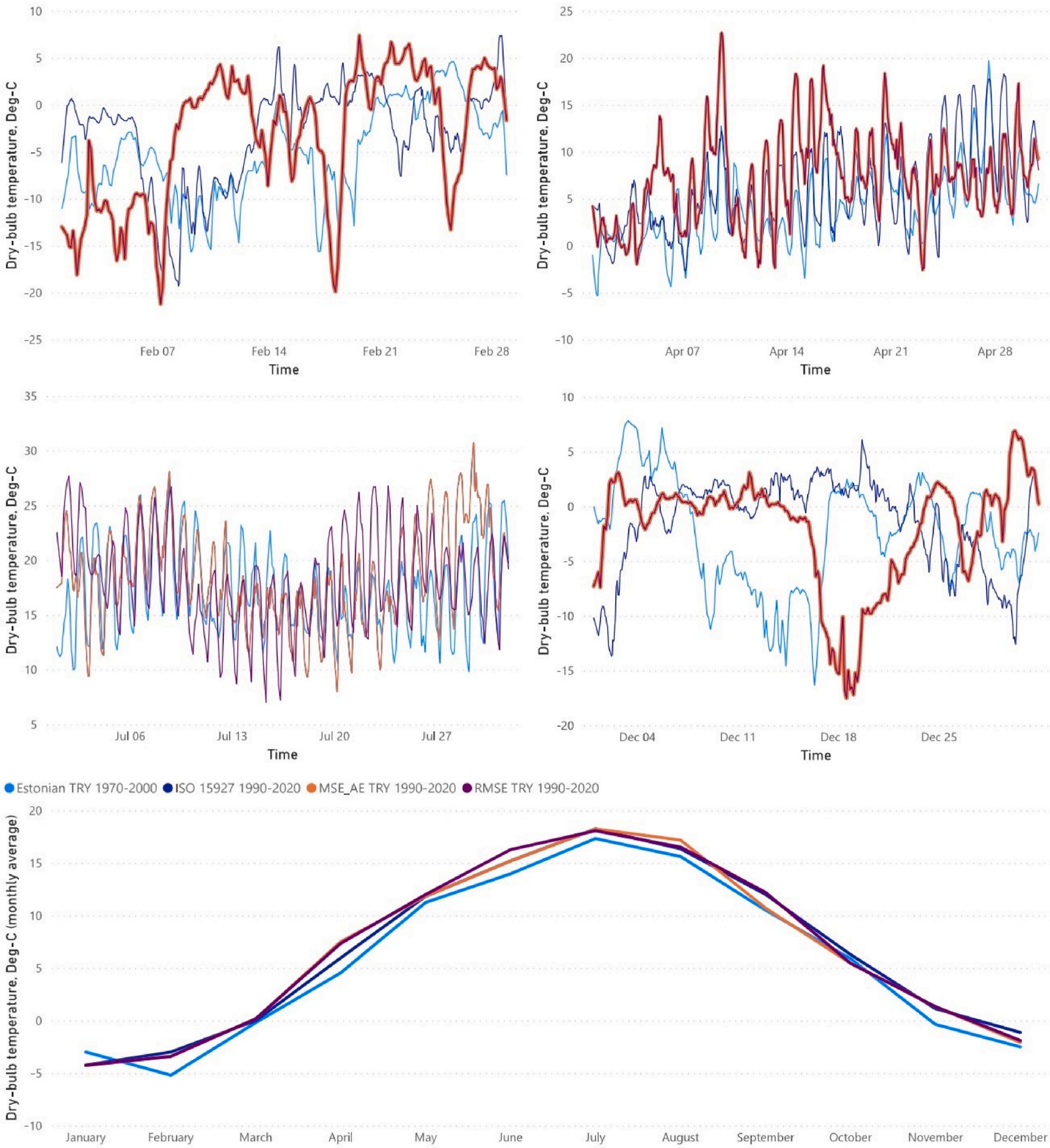

Fig. 9. Dry-bulb Temperature for selected TMYs and selected months. The upper charts present hourly temperature values for February, April, July, and December. Lines that are over each other became thicker. The lower chart presents the daily average temperature for the whole year.

separately and combining them with weighting factors to assemble a Typical meteorological year.

The method compares the monthly energy need simulation results to the 31-year simulation results and, using a statistical method, chooses the best month/year combination among 31 possible choices and creates the year by combining those month/year data. Using this procedure, there is no need to find and define weighting factors to improve accuracy, and it is also more accurate compared to the standard method without the weighting factor.

The three main methods evaluated in this study, namely the original EN ISO 15927-4 method [14], the same method with weighting factors, and the method suggested in this article, showed some significant differences. EN ISO 15927-4 [14] had the highest average deviation of 5 % for heating and 7 % for cooling, followed by the same method, with weighting factors varied by 4 % for heating and cooling. However, the method proposed in this article had the lowest average deviation within

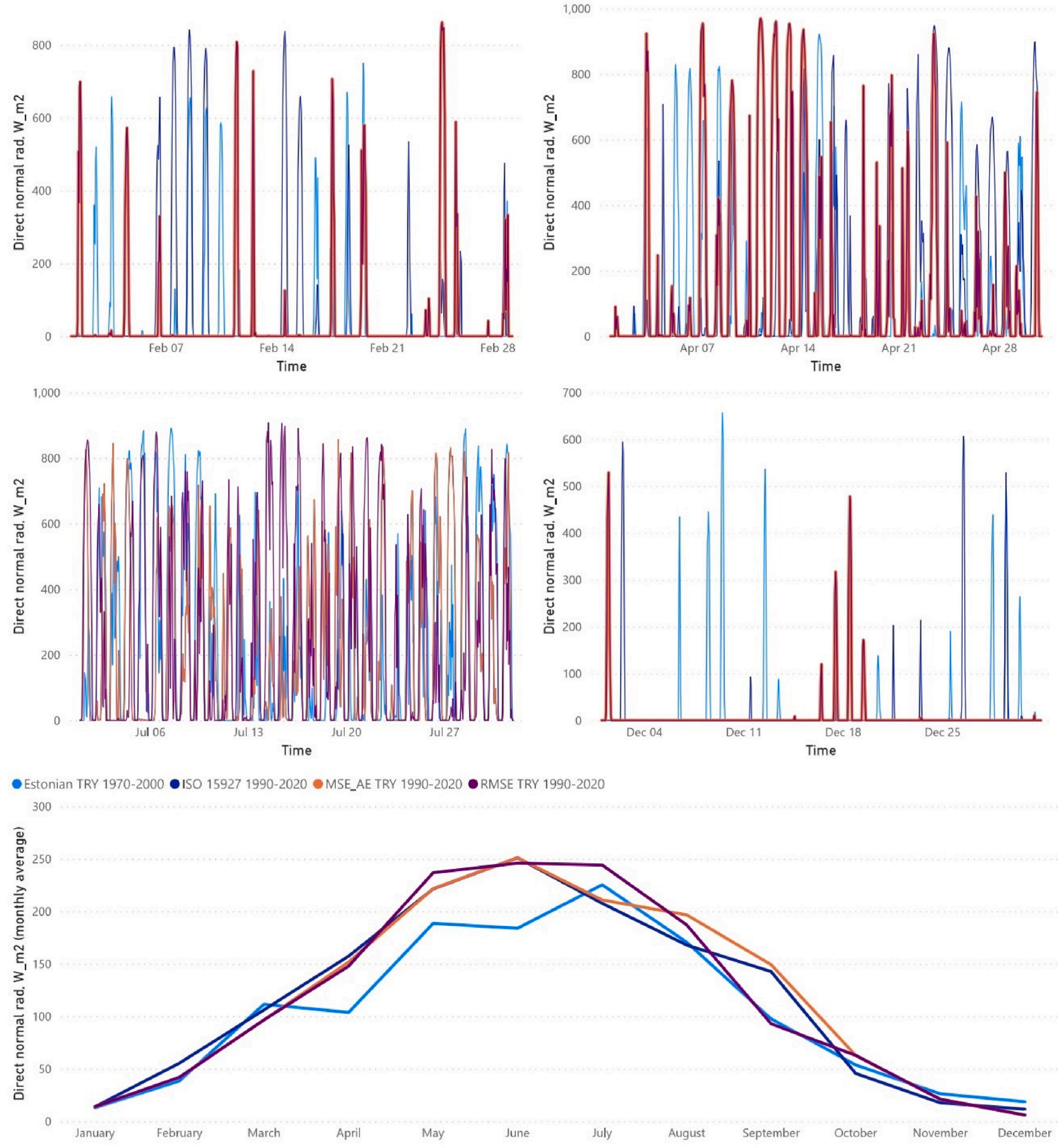

Fig. 10. Direct Normal Radiation for selected TMYs and selected months. The upper charts present hourly direct normal radiation values for February, April, July, and December. Lines that are over each other became thicker. The lower chart presents the daily average direct normal radiation for the whole year.

1 % for heating and, on average, 4 % for cooling. These findings imply that the method developed may be more accurate for energy simulations than the other two methods. Comparison between methods for heating degree days and cooling degree hours shows that the method developed reflected the summer situation adequately, while the numbers for heating degree days were close for different methods.

Among the statistical methods, the MSE_AE method (mean square error normalized by average annual heating and cooling need) was selected because it delivers low marginal deviation compared to 31 years simulations while cooling need values are 4–6 % higher than the average of 31 years. The heating needs were the same, or a little lower during the winter, which can also reflect long-term global warming effects since it is continually decreasing the energy need during the winter and increasing the energy need during the summer in the Estonian context. In addition, the deviation estimates are consistent amongst various reference building scenarios.

This work shows that long-term energy simulations with current weather data and building methods that match current practices could indirectly account for the importance of climate parameters in TMY generation. The developed TMY generation method has wide application potential and is recommended for testing and validation in other climates.

CRediT authorship contribution statement

Seyed Shahabaldin Seyed Salehi: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis. **Targo Kalamees:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Jarek Kurnitski:** Writing – review & editing, Supervision. **Martin Thalfeldt:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix

Table 1
Top 3 ranked months using ISO 15927-4 method with weighting factors [17]. The horizontal title is the weighting factor for temperature. The radiation weighting factor is subtracted from the temperature weighting factor from 1.

Month/w	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
01	01–2019	01–2019	01–2017	01–2017	01–2017	01–2017	01–2017	01–2017	01–2017	01–2017	01–2017
	01–2004	01–2017	01–2008	01–1999	01–1999	01–1999	01–1999	01–1999	01–1999	01–1999	01–1999
	01–2008	01–2008	01–2007	01–1997	01–1997	01–1997	01–1997	01–1997	01–1997	01–1997	01–1997
02	02–2019	02–2019	02–2019	02–2019	02–2009	02–2009	02–2009	02–2009	02–2009	02–2009	02–2009
	02–2009	02–2009	02–2009	02–2009	02–2013	02–2013	02–2013	02–2013	02–2013	02–2013	02–2013
	02–2017	02–2017	02–2017	02–2017	02–2017	02–2017	02–2017	02–2017	02–2017	02–2017	02–2017
03	03–2016	03–2016	03–2016	03–2016	03–2016	03–2016	03–2016	03–2016	03–2016	03–2016	03–2016
	03–2019	03–2019	03–2019	03–2012	03–2012	03–2012	03–2012	03–2012	03–2012	03–2012	03–2012
	03–2012	03–2012	03–2012	03–2001	03–2001	03–2004	03–2004	03–2004	03–2004	03–2004	03–2004
04	04–2016	04–2016	04–2016	04–2016	04–2016	04–2016	04–2016	04–2016	04–2016	04–2012	04–2012
	04–2012	04–2012	04–2012	04–2012	04–2012	04–2012	04–2012	04–2012	04–2012	04–2015	04–2014
	04–2006	04–2006	04–2006	04–2006	04–2006	04–2006	04–2015	04–2015	04–2015	04–2002	04–2015
05	05–2020	05–2020	05–2020	05–2020	05–2020	05–2020	05–2020	05–2020	05–2020	05–2014	05–2014
	05–1990	05–1990	05–1990	05–1990	05–1990	05–2008	05–2008	05–2008	05–2008	05–2020	05–2020
	05–2008	05–2008	05–2008	05–2008	05–2008	05–2011	05–2011	05–2011	05–2011	05–2008	05–2008
06	06–2020	06–2005	06–2005	06–2005	06–2005	06–2005	06–2005	06–2005	06–2005	06–2005	06–2005
	06–2005	06–2013	06–2013	06–2016	06–1997	06–1997	06–1997	06–1997	06–1997	06–1997	06–1997
	06–2013	06–2002	06–2016	06–2002	06–2016	06–2016	06–2018	06–2018	06–2018	06–2018	06–2018
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08	08–2020	08–2019	08–2016	08–2016	08–2016	08–1999	08–2016	08–2015	08–2015	08–2015	08–2015
	08–2019	08–2016	08–2018	08–2018	08–2018	08–2016	08–2004	08–2016	08–2016	08–2016	08–2016
	08–2018	08–2018	08–2004	08–2004	08–2004	08–2011	08–2011	08–2004	08–2004	08–2004	08–2004
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	12–2014	12–2014	12–2014	12–2014	12–2014	12–2014	12–2020	12–2008	12–2008	12–2008	12–2008

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Appendix 2

II

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Cooling design day generation methods' and risk levels' impact on the design capacities and risk of thermal discomfort in a cold climate

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ABSTRACT

Meteorological data is needed to determine the size of the cooling/heating systems. A design day is commonly used for cooling. ISO 15927-2 and the ASHRAE handbook provide comprehensive guidelines for generating design day weather data with different risk levels. However, the impact of different risk levels and design day generation methods on thermal discomfort has been rarely quantified. This study integrated design day analysis with long-term thermal comfort simulations to assess the cooling system design capacities obtained using design days generated by the aforementioned methods and different risk levels in the temperate and mild climate of Estonia. A generic open-plan office was used for sizing cooling units and subsequently for thermal comfort assessment based on long-term historical data. The ASHRAE Fundamentals method performed better in Estonia's climate, whereas ISO 15927-2 needs further development to avoid reaching controversial results among risk levels. Solar radiation and internal heat gains contributed most to the space cooling capacity, and the differences between the design capacities for the risk levels were negligible. The space cooling temperature setpoint of 25 °C was rarely or never exceeded by more than 0.5 °C in long-term simulations, except in the North-oriented zones. Therefore, a risk level of 10 % was recommended for sizing space cooling without significantly increasing the risk of thermal discomfort. Ventilation supply air cooling capacity depends more on the enthalpy of outdoor air, and therefore, a risk level of 5 % is recommended.

1. Introduction

Buildings account for approximately 28 % of global energy-related greenhouse gas emissions [1]. Therefore, improving buildings' energy efficiency and optimal use of resources during construction are essential to minimize our contribution to global warming. Outdoor climate input data is crucial in energy simulations and estimating a building's energy use, as it is an integral aspect of designing an energy-efficient building. Accurate meteorological data is necessary for designing cooling/heating systems and estimating buildings' annual energy demand. Multiple studies have been carried out to gather meteorological data for indoor climate and energy simulations. If there is no hourly database for the site, only limited forms of meteorological data may be provided. This could include average values derived from an existing database or simulated data generated by a program using predefined models [2].

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Nevertheless, there is an abundance of hourly meteorological data available for numerous locations worldwide.

A design day represents critical conditions used in building performance simulations for sizing heating, ventilation, and air conditioning (HVAC) systems. It is created based on statistical weather data to reflect peak heating or cooling loads, ensuring that systems are adequately sized for worst-case scenarios [3]. The process of generating design day data for sizing cooling and heating systems began in the 20th century [4]. Design day data is crucial for accurately designing building heating and cooling systems, which contains the anticipated upper and lower temperature limits, levels of humidity, and solar radiation for a particular geographical point on the hottest and coldest days of the year. During the mid-20th century, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) initially established design conditions for different locations in the United States [5]. ASHRAE, the International Energy Conservation Code (IECC), and the European Committee for Standardization (CEN) have subsequently released guidelines and standards for determining design day data in different global regions. Accurate calculation of design day data is crucial for achieving the best possible design and operation of heating and cooling systems [6,7].

Yuan et al. [8] concluded that using the conventional method for designing air conditioner size overestimates the cooling capacity. Chen et al. [9] argued that using ASHRAE and historical weather data results in an oversized air conditioning system. In another article [10], the writers provide rational selection methods for risk-based air conditioning design. Fang et al. [11] provided correction coefficients for the coincident design day method, and the peak cooling load from CDD matched the actual design load within 5 % in over 90 % of atypical cases in the study. Multiple studies propose potential future scenarios, validate calculation methods for design days, or offer alternatives to conventional design day methods. Farahani et al. demonstrated the variability in dimensioning outcomes under different future climate scenarios in the Finnish climate, which resembles Estonia [12]. Carlucci et al. [13] reviewed numerous articles that employed data-driven models and machine learning-based approaches to accurately model occupant behavior and forecast the loads required for system sizing.

Pezzi et al. [14] evaluated the quality and effectiveness of the design day selection using the EN ISO 15927-2 standard. They investigated the performance of this method across 108 locations in Italy and identified key shortcomings. Their study employed sensitivity analyses to assess the impact of various climatic parameters (temperature, solar radiation, and dew-point temperature) on the design days. They observed counterintuitive results, such as higher required powers for lower risk levels, and highlighted the negligible impact of wind speed on the selection process. Pezzi et al. [14] reformulated the standard into a simplified "Coordinates Method" for automation, but concluded that the current EN ISO 15927-2 implementation often fails to ensure reliable cooling sizing. Their analysis revealed that when different sets of climatic parameters were considered for design day generation (temperature and radiation are obligatory, while dew point, wind, and daily temperature range are optional to include), the selected design days showed significant variability, with less than 20 % of the days overlapping across different parameter sets. This means that the design day selection process can be subjective since the sets of parameters involved in a specific design day generation process can vary and depend on the practitioner's decision. However, since they concluded that wind speed had minimal impact on the selection process, over 90 % of the selected design days remained consistent when wind was the only parameter that varied. This aligns with ASHRAE [3], as this method does not involve wind in the primary selection procedure. Fang et al. [15] developed a method based on clustering to determine the coincident design day, rather than using standard methods. Zhang et al. [16] compared the radiant and conventional time series methods for determining the design day, finding the radiant time series method to be the more favorable approach for radiant cooling systems.

Traditionally, thermal comfort in buildings has been assessed using models such as the Predicted Mean Vote (PMV), developed by Fanger [17]. These models are designed to predict the average thermal sensation of occupants, providing a basis for designing HVAC systems to maintain comfortable indoor conditions. On the other hand, Methods like the TAIL method [18] and EN 16798–1:2019 [7] provide frameworks for defining and evaluating thermal comfort in buildings using temperature. TAIL [18] uses indoor air temperature to assess thermal comfort. The air temperature criteria of this method for the best building category ranged between 23.5 °C and 25.5 °C. According to the method, temperatures may surpass the specified range by up to one category for a maximum of 5 % of the occupancy time and by up to two categories for no more than 1 % of the time when measurements were taken (i.e., during office hours in workplaces and nighttime hours in hotels). This approach, which assesses the percentage of occupancy time when temperatures exceed the recommended thresholds, aligns with the method suggested by the Level(s) framework [19]. EN 16798-1 [7] uses operative temperature for thermal comfort classification of buildings. In contrast, the TAIL system uses air temperature, justifying it because the difference between air and operative temperature is low in low-energy buildings.

While design days are generated for different risk levels to account for extreme weather conditions, there is limited research on how these varying risk levels impact the sizing of different cooling system components and, consequently, thermal comfort. Complementary evidence from a stock-scale, parametric study of secondary schools in southern Spain shows that ventilation rate and solar exposure (orientation, shading) dominate comfort outcomes [20], reinforcing our choice to evaluate sizing decisions against long-term comfort metrics rather than peak loads alone.

This study aims to build evidence for proper risk level selection, as it remains unclear how system sizing, determined by different risk levels in design day data, affects thermal comfort during operation. Specifically, understanding the impact of system sizing according to various risk levels on thermal comfort is crucial for optimizing system performance and cost.

This study uniquely integrates design day analysis with long-term thermal comfort simulations using multi-decade climate data to address the research gap by:

- Analyzing design days generated for different risk levels and their impact on the design cooling capacities of various cooling system components – the cooling plant, room units, and air handling unit (AHU) cooling coils.
- Assessing thermal comfort using a specifically developed method to understand the implications of system sizing decisions.

- Using a generic open-plan office floor with greatly varied window sizes, properties, and shadings to show the sensitivity and ensure that results can be generalized for non-residential buildings.

By exploring these aspects, the research aims to provide more precise guidance on selecting appropriate risk levels for design day generation, ensuring optimal cooling system design that mainly considers thermal comfort. This paper presents a critical comparison of the methodologies employed in developing design days for cooling systems, utilizing data from the Estonian climate and the most recent cooling design days developed for Estonia. Simulations of a generic open-plan office with zones oriented towards the four main directions, situated on the middle floor of a building, were conducted to analyze and provide suggestions for selecting a design day for sizing cooling systems in Estonian buildings. Finally, long-term simulations were conducted for a few cases to assess thermal discomfort across all risk levels specified in the standards.

The analysis involved evaluating temperature data over time to determine the occurrence and severity of overheating in various zones. This was done by comparing the simulated hourly room temperatures against predefined thresholds for different risk levels. This assessment analyzed the impact of different risk levels, as defined by ASHRAE [3], on simulation results for sizing and subsequent thermal comfort. The method described in ISO 15927-2 [18] was also used to develop design day data, which is presented in this study.

Despite the growing importance of thermal comfort assessment in long-term simulations, a lack of robust methodologies remains for evaluating comfort under extreme climatic conditions over longer historical periods. In this study, the evaluation of prolonged overheating involves the analysis of various measurements, including the number of hours the temperature exceeds a specific threshold, the frequency of days with temperatures surpassing the threshold, and the maximum deviations of temperature from the desired range during the assessment period. Moreover, the study assessed the influence of various design cooling capacities on discomfort by comparing the simulation results using the above-mentioned procedures.

The analysis has also assessed the percentage variation in discomfort metrics, such as the duration of discomfort and the frequency of discomfort events, in relation to the capacity of the cooling system. The study aims to assess the impact of system sizing on thermal comfort by quantifying the percentage change in these metrics as the size of the system varies.

Ultimately, this assessment helped to reflect on the relationship between selecting various risk levels and the dimensions of room units and cooling coil capacities of air handling units (AHUs), consequently affecting the investment cost of the cooling system and overall thermal comfort in the office setting.

2. Methods

The methodology of this study comprises the generation of design days using established standards, the sizing of cooling system components through dynamic simulations, and the evaluation of the thermal comfort performance of these systems during the heat waves that occurred between 1990 and 2022 in Tartu, Estonia (58°22′ N, 26°43′ E), a humid continental climate (Dfb) with cold winters and mild to warm summers. The climate is thus characterized by moderate latent loads but large seasonal temperature amplitude, making it a representative test case for northern-European cooling design and comfort analysis. All the simulations are done in IDA ICE 5 [21] software.

The activities listed below are a brief description of the process of this analysis.

1. Generating design days with different risk levels defined in relevant standards (ASHRAE [3] and ISO 15927-2 [22] for detail, see 2.1)
2. Developing a generic open-plan office floor as the reference building and sizing the cooling plant, AHU cooling coil, and room units with varied conditions for window size, sunlight direction, and shading (16 cases in total) using dynamic simulations based on the identified design days for all risk levels. (see 2.3)
3. Conducting long-term simulations with historical weather data to analyze room temperatures using the cooling system components' sizes derived in the previous step.
4. Assessing the impact of risk levels on thermal comfort during historical heat waves by assessing maximum room temperatures and quantifying the number of occupied hours with a temperature higher than the maximum allowed in every classification defined by the standard (TAIL [18] and EN 16978-1 [7] for details, see 2.2).
5. Discussion and recommendations for the best practices in sizing different cooling system components, considering thermal comfort.

2.1. Design day generation method

In this study, we used two design day generation methods

1. The ASHRAE fundamental method for generating design day [3].
2. The ISO 15927-2 for generating design day [22].

For both methods, historical weather data from the Tartu region in Estonia were used. The data included hourly measurements of dry-bulb temperature, diffuse and direct solar radiation, relative humidity, wind speed, and wind direction. The generated design days based on each method were then used for further analysis in the study. A schematic flow of the methods is provided in Fig. 1, where common stages (precisely the same in both methods) and similar stages (same principle with different implementation procedures) are colored. Below is a summary of each method:

2.1.1. Design day, according to ASHRAE

Design day consists of hourly data for a single day, including main parameters (dry-bulb and wet-bulb temperature) and additional parameters (wind and radiation)

1. Gathering historical weather data for the studied region.
2. Identifying dry-bulb and wet-bulb temperatures representing three frequencies of occurrence (0.4 %, 2 %, 5 % and 10 % named as risk levels).
3. Identifying wind speed corresponding to the dry-bulb temperature with a 5 % frequency of occurrence.
4. Theoretical calculation of the radiation for the specific location, based on its latitude, longitude, and height, with a clear sky.

2.1.2. Design day, according to ISO 15927-2

According to ISO 15927-2, design day is also hourly data for a single day. Mandatory parameters are temperature and radiation. Other parameters can be included if needed, as described in the second step.

1. Gathering historical weather data for the studied region.
2. Identifying the parameters needed to generate the design day. Temperature and radiation are mandatory parameters; we chose to have dew point temperature in this study to have a more comparable result with ASHRAE.
3. Identifying mean daily dry-bulb and dew-bulb temperature and total global irradiation representing three frequencies of occurrence (1 %, 2 % and 5 % named as risk levels).
4. Identification of the design day:
   a. Start with an initial error range (error band) for each parameter, as defined by the standard
   b. For each calendar month and risk level, identify days where the daily average values of all parameters fall within this initial error range.
   c. If only one day meets the criteria, that day is selected as the design day.
   d. If multiple days meet the criteria, progressively narrow the error range until only one day is left.
   e. If no days meet the criteria, gradually widen the error range until a suitable design day is identified.

The error ranges for identifying design days in ISO 15927-2 are defined for each parameter and adjusted iteratively during selection. For all temperature-related parameters (e.g., dry-bulb temperature, dew-point temperature), the error range is defined with Formula 1, and for global radiation, Formula 2.

$$Range = 0.5\ \pm X \cdot 0.1 \tag{1}$$

$$Range, rad = 50\ \pm X \cdot 10 \tag{2}$$

Where X represents the iteration interval, consistent across all parameters, X is incremented by 1 in each step, progressively widening the error band when no suitable day is found within the current range. During the selection process, daily averages of all parameters are evaluated against these ranges for each calendar month and risk level. If multiple days meet the criteria, the process narrows the error range (decreasing X) until only one day remains. Conversely, if no date meets the initial criteria, X is incremented to expand the range iteratively. This ensures that a design day is selected for each scenario while minimizing subjectivity and maintaining consistency across parameters.

As it is written in Fig. 1, the standards have different risk levels. While both have 2 % and 5 %, ISO does not cover any lower risk class, as ASHRAE has 10 %, and the strictest risk level of ISO is 1 %, while it is 0.4 % for ASHRAE.

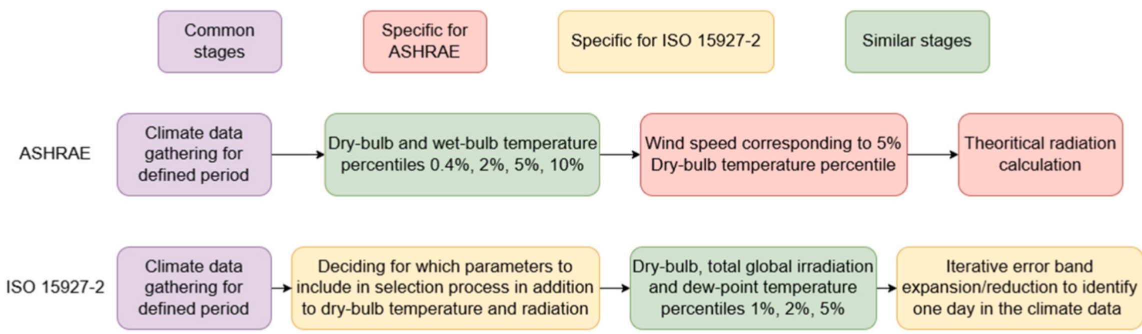

Fig. 1. Schematic view of the design day generation methods.

2.2. Thermal comfort requirements and sizing methodology

In order to assess the effectiveness of the design day methods and risk levels, a simple assessment method is developed in this paper. The method requirements follow the TAIL method [18] with compliance with the EN 16798–1:2019 method [7] on the thermal comfort of the occupants.

As mentioned in the introduction, the TAIL method [18] specifies acceptable temperature ranges and exceedance limits, focusing on the percentage of time temperatures can deviate from optimal thresholds. EN 16798–1:2019 [7] has a broader approach by categorizing indoor environments and standardizing thermal comfort criteria. In this work, the indoor air temperature is used for the analysis, supported by a rule of thumb confirmed by Wagocki et al. [18] and provided simulation results in this paper, where the difference between operative and air temperature can reach up to 1 °C in the simulation models.

The design air temperature for sizing and the thresholds for assessing thermal discomfort used in this study were 25 °C. Additionally, 25 °C is the temperature setpoint for modeling Estonia's energy use of non-residential buildings [23]. To summarize the paper's approach to thermal discomfort assessment, the following list can be provided:

- The total hours during the simulated period when the air temperature exceeded the 25 °C threshold.
- The number of hours in a continuous 30-day period with temperatures surpassing the 25 °C thresholds according to TAIL criterion of 5 % accepted excess by 1 °C.
- The maximum temperature deviations above the threshold during occupied hours.

To justify the 25 °C air temperature setpoint, we rely on the following reasoning:

- Category II is the default standard for new buildings according to EN 16798-1 [7].
- The upper limit of 26 °C for operative temperature in Category II can be met with a 25 °C air temperature setpoint, assuming a maximum 1 °C difference between air and operative temperature.
- In this analysis, compliance with Category II is the primary objective, allowing 5 % of the time to be in Category III, meaning air temperature should remain below 26 °C.

2.3. Building simulation model

Building thermal and comfort analyses were performed in IDA ICE 5 [21] software. A dynamic multi-zone simulation environment widely validated for HVAC design and comfort research. IDA ICE solves coupled heat-and-mass balance equations for each zone using an implicit variable-time-step differential–algebraic (DAE) solver based on IDA Solver [24]. The model represents each room as a well-mixed thermal zone with conductive heat transfer through envelope elements, radiative exchange, internal gains, and air-handling unit (AHU) and room-unit coils modeled as component networks with integrated control loops. The solver automatically adjusts time steps to maintain numerical stability and energy balance, enabling accurate representation of both transient internal loads and daily outdoor variations.

The building body specification and the general plan view of the offices are shown in Fig. 2, and the three-dimensional view of different windows and shading alternatives is shown in Fig. 3. The occupancy schedule and fan operation schedule are shown in Fig. 4, and the air handling unit has an air-to-liquid cooling coil. The same model has been used in another study in 2021, where the writers

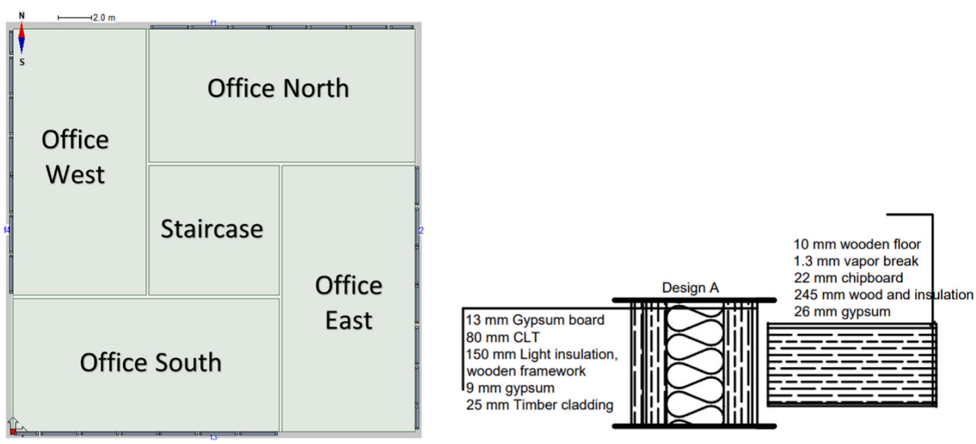

Fig. 2. General office plan (left), 24.5m x 24.5m. Structural properties of the building (right). CLT in wall composition is an acronym of Cross-Laminated Timber.

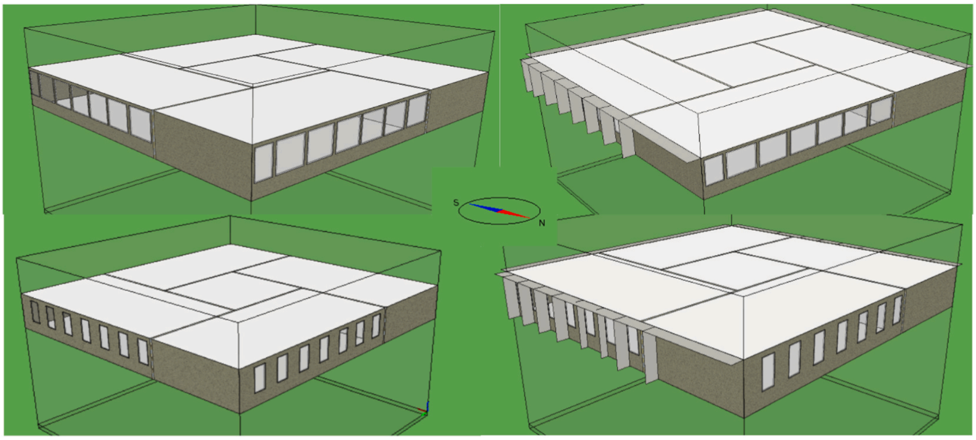

Fig. 3. 3D view of the models with two different Window-to-Wall Ratio (WWR) and shading.

showed that the impact of structural weight on sizing systems is negligible [25]. The material properties of each layer in the structure are from the IDA ICE material database [21]. Several parameters were determined based on EN 16798-1 [7] or were based on assumptions to facilitate the study. These parameters were as follows:.

- The supply air temperature setpoint was 17 °C,
- The offices and the staircase had balanced mechanical ventilation with a specific air flow rate of 1.4 l/(m^2·s) during working hours, with 1 h margin. The flow outside of the working hours is the minimum amount (0.21 l/(m^2·s)) to consider the ventilation of toilets, cleaning equipment room, etc. ventilation working on part load. No natural ventilation is modeled other than infiltration mentioned in Table 1.
- The room temperature setpoint was 25 °C,
- The heat exchange between rooms happens only through internal walls. Internal walls were modeled as 30 mm light insulation and 52 mm gypsum with a U-value equal to 0.62 W/(m^2.K). Detailed window and building specifications are written in Table 2 and Table 3 respectively.
- The office is located in Tartu, Estonia.

The layout includes four offices with dimensions of 16m x 8m and an area of 128 m^2. The offices were 3 m high. The office used in this simulation is located on a middle floor with adiabatic internal floors. The cooling devices in all zones were ideal coolers with a coil temperature of 15 °C.

The sizing procedure started with modeling ideal coolers with unlimited capacity in all zones, together with an air handling unit and a chiller with very large capacities. Using generated design days for every month based on the two above-mentioned methods, iterative simulation has been done, and maximum capacities for the cooling device, air handling unit cooling coil, and the cooling plant (which is the accumulated simultaneous cooling need of both air handling unit and zone devices) have been derived from models for each building type. The resulting capacities were then re-entered in models and long-term simulations conducted with climate data of Tartu from 1990 to 2022. Simulations logged hourly air temperatures and cooling device outputs to evaluate the system's ability to maintain thermal comfort and meet cooling demands.

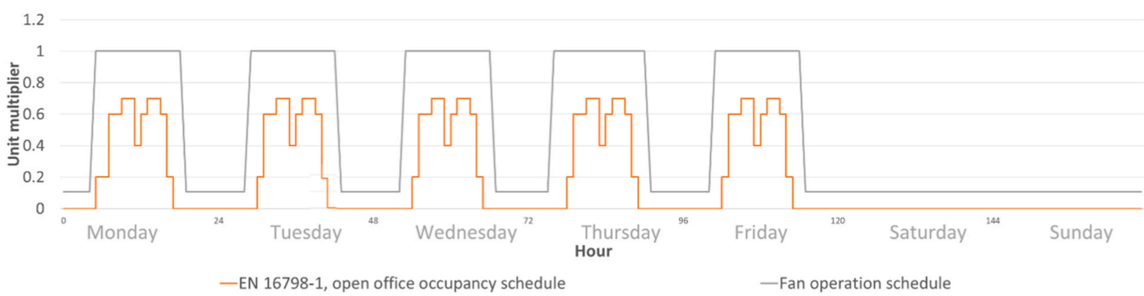

Fig. 4. The occupancy and fan operating schedules used in this study.

Table 1
Parameters used in the simulations of the reference buildings.

Parameter, Unit	value
Gross area, m^2	512 + 88
Occupants, person/m^2	0.09375
Equipment, W/m^2	12
Lighting, W/m^2	6
Ventilation airflow rate, L/(s·m^2)	1.4
Infiltration constant air flow rate, L/(s·m^2)	0.056
Thermal transmittance External walls, W/(m^2·K)	0.2

Table 2
Windows specifications.

Parameter, Unit	1 (small)	2 (big)
Width, m	1.8	2.1
Height, m	1	1.9
Area, m^2	1.8	3.99
Window to wall ratio, -	0.25	0.58
Total windows per office, -	7	7
Number of panes, -	3	3
Solar heat gain coefficient, -	0.49	0.32
Solar transmittance, -	0.41	0.28
Visible transmittance, -	0.71	0.59
Glazing thermal transmittance W/(m^2·K)	0.6	0.6
Internal emissivity, -	0.837	0.837
External emissivity, -	0.837	0.837
Frame ratio, -	0.1	0.1
Frame thermal transmittance W/(m^2·K)	2	2

3. Results

3.1. Difference between dry-bulb and operative temperature

The space cooling room units in this study were controlled according to dry-bulb temperature to mimic the behavior of an actual cooling system. The room temperature setpoint was 25.0 °C, that is 0.5 °C below the EN 16798–1:2019 II category limit of 25.5 °C. As the thermal comfort was assessed based on dry-bulb temperature, the differences between dry-bulb and operative temperatures were identified. The occupants in the zone were placed in the exact middle of each zone. Fig. 5 shows the results from the 15^{th} of July 2018, which was one of the days with a high difference between the air and operative temperatures. The difference between zone air temperature and the operative temperature in the zones could be up to 1 °C for short periods, depending on the critical position of the occupant in the simulation model used. Therefore, the selected temperature difference of 0.5 °C is a reasonable approach for this study.

3.2. Design day generation results

The design days generated parameters using ASHRAE [3] are presented in Table 4. DB is an abbreviation for Dry-Bulb temperature, and WB represents Wet-Bulb temperature. An illustration for July is given in Fig. 6 _with calculated enthalpy instead of wet bulb_ to facilitate the comparison between risk levels by the readers. The required climate parameters were calculated for specific risk levels 0.4 %, 2 %, 5 % and 10 %, representing the frequency of occurrence of extreme conditions. The 0.4 % risk level corresponded to the strictest conditions, while the 5 % level reflects more moderate scenarios. The maximum dry-bulb temperature in July reaches 29.8 °C for the 0.4 % risk level, compared to 28.2 °C and 26.4 °C for the 2 % and 5 % levels, respectively. 10 % has the lowest temperature among all, which is 24.6 °C. Wet-bulb temperatures, on the other hand, show less variation across risk levels, with a maximum value of

Table 3
Building specifications, office.

Structure	Office, big windows Area (A), m^2/Specific heat loss (H), W/K	Office, small windows Area (A), m^2/Specific heat loss (H), W/K
External wall	A = 177.8/H = 35.56	A = 237.6/H = 47.52
Windows	A = 110.2/H = 66.12	A = 50.4/H = 30.24
Specific heat loss for heated area H/A, W/(m^2·K)	0.2	0.15
Total specific thermal transmittance, U·A (W/K)	180.7	138.2

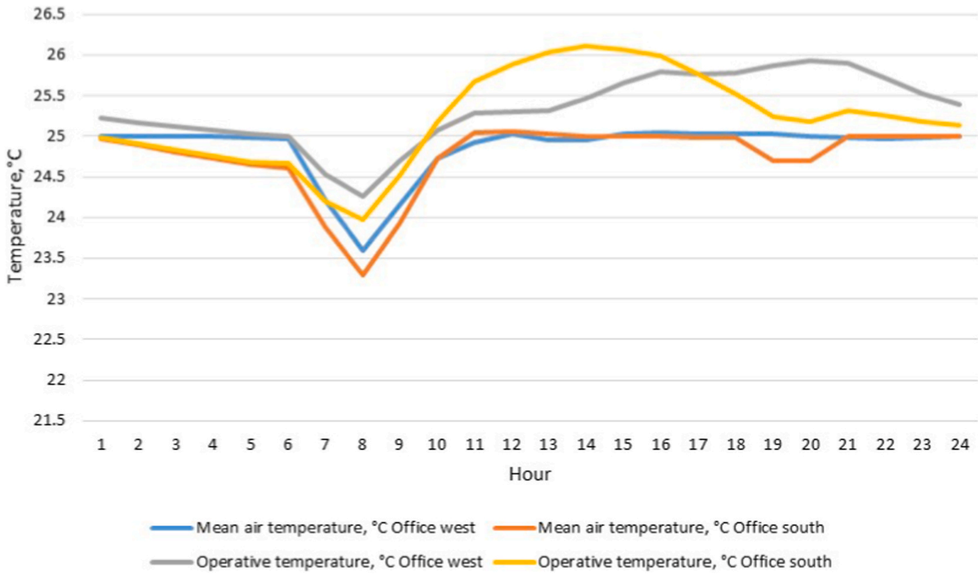

Fig. 5. Mean air temperature and operative temperature of selected zones in the warmest conditions in the model with big windows and no shading.

Table 4
Design days parameters based on ASHRAE [3], the thick line is on July design days, illustrated in Fig. 6.

Month	wind speed m/s	0.4 % percentile, strictest			2 % percentile, strict			5 % percentile, moderate			10 % percentile, moderate		
		DB Max °C	DB Min °C	WB °C	DB Max °C	DB Min °C	WB °C	DB Max °C	DB Min °C	WB °C	DB Max °C	DB Min °C	WB °C
1	4.6	6.3	1.7	5.8	5.0	0.4	4.3	3.9	−0.7	3.2	2.7	−1.9	2.1
2	4.3	6.8	1.9	5.5	5.1	0.2	3.7	3.7	−1.2	2.8	2.9	−2.0	2.1
3	3.9	12.1	5.2	7.2	9.8	2.9	5.6	7.5	0.6	4.5	5.8	−1.1	3.5
4	3.3	21.1	11.9	12.0	17.6	8.4	10.2	14.6	5.4	8.7	12.4	3.2	7.3
5	3.3	27.4	18.4	18.3	24.4	15.4	16.6	21.6	12.6	15.3	19.4	10.4	13.8
6	2.1	30.2	23.2	22.3	27.7	20.7	20.8	25.3	18.3	19.3	23.1	16.1	17.8
7	4.9	29.8	24.1	22.4	28.2	22.5	21.0	26.4	20.7	19.9	24.6	18.9	18.9
8	2.9	29.9	23.6	21.1	27.6	21.3	19.7	25.2	18.9	18.8	22.9	16.6	17.8
9	2.7	24.3	17.6	18.3	21.3	14.6	16.8	19.3	12.6	15.7	17.6	10.9	14.6
10	6.3	16.0	9.4	13.8	14.2	7.6	12.2	12.7	6.1	11.3	11.8	5.2	10.4
11	5.8	11.5	6.1	10.5	9.8	4.4	8.8	8.6	3.2	7.7	7.5	2.1	6.6
12	6.3	8.9	2.0	7.9	6.7	−0.2	5.9	5.4	−1.5	4.7	4.2	−2.7	3.6

22.4 °C for the 0.4 % risk level, underlining the stability of this parameter in the ASHRAE method. IDA ICE calculated the radiation parameter in the ASHRAE method generically [21]. The parameter is calculated using the location-specific and atmospheric data and does not vary between risk levels. The design days parameters based on ISO 15927-2 [16] are listed in Table 5 and illustrated in Fig. 7. Unlike the ASHRAE method, where dry-bulb and wet-bulb temperature trends align logically across risk levels, the ISO method yields results where critical days show discrepancies, such as reversed radiation trends. For example, while the mean dry-bulb temperature increases from 10 % to 0.4 % risk levels, the radiation data does not follow the same trend, with some risk levels showing lower radiation for stricter thresholds. The total radiation on the horizontal surface using both methods is shown in Fig. 8.

A detailed look into the daily parameters generated using an interpretation of the ISO 15927-2 [22] method by the Authors of this study enables the reader to understand the inconsistency in the values. The total global radiation for 1 % is mostly lower during the day, while it has the maximum peak among other risk factors. This is not the case for temperature. The daily temperature trends show higher temperatures for 5 % compared to 2 %, while 1 % temperature data points show generally higher values. Humidity, the main parameter for designing the AHU cooling coil, also shows inconsistencies.

Another aspect can be analyzed using the selected design days for June. As mentioned in the standard, the intervals for increasing the span of dry-bulb temperature maximum and minimum differences, together with global irradiation and dew point, shall be adjusted until one day is identified from the historical data. The selected days for all risk levels in June are presented in Fig. 9. The mean values of dry bulb temperature and dew point temperature align with the general trend of the risk levels, while the radiation data are reversed. This was due to the need for a wider error band to include a day where all parameters are inside the bands. The wider the error bands are, the more the chosen day's daily averages can fall into broader possibilities, like 1 % selected day, which requires about

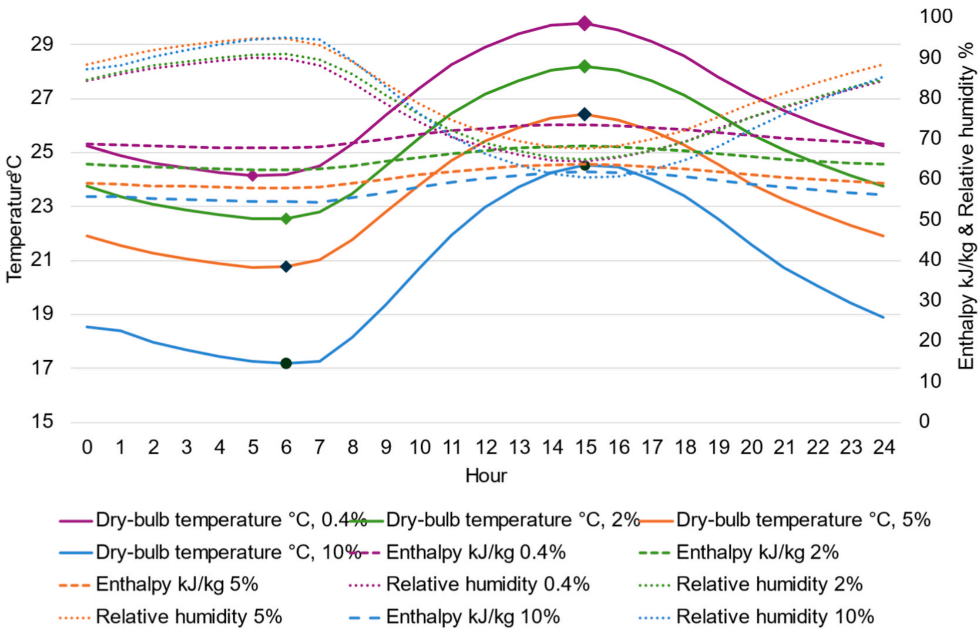

Fig. 6. Dry-bulb air temperature and design wet-bulb temperature for the design days of July for different risk factors using ASHRAE method.

Table 5
Design days parameters based on ISO 15927-2, thick line is on July design days, illustrated in Fig. 7.

Month	1 % percentile, strictest				2 % percentile, strict				5 % percentile, moderate			
	DB Max °C	DB Min °C	WB °C	wind speed m/s	DB Max °C	DB Min °C	WB °C	wind speed m/s	DB Max °C	DB Min °C	WB °C	wind speed m/s
1	8.3	1.3	7.2	6.0	7.2	1.2	6.0	6.0	4.4	1.2	3.2	6.0
2	10.1	0.5	8.4	3.3	8.4	1.0	6.5	5.2	5.4	1.0	3.8	5.2
3	12.1	4.1	7.8	3.4	10.3	4.1	6.1	3.4	6.6	4.1	3.2	2.7
4	21.9	12.5	13.7	2.5	18.9	12.1	11.3	2.5	14.9	12.1	7.4	2.5
5	27.1	16.1	20.6	3.1	23.9	16.5	17.8	2.2	20.0	16.5	13.3	2.2
6	30.7	18.5	24.0	1.5	20.5	19.5	13.4	1.2	23.8	19.5	17.8	1.0
7	27.6	23.2	21.5	1.9	26.9	22.9	20.5	3.4	25.4	22.9	19.1	2.5
8	27.6	20.8	21.4	1.2	25.7	21.1	19.7	2.0	23.1	21.1	17.6	2.3
9	21.4	16.6	17.3	1.7	19.9	16.3	16.1	1.7	18.8	16.3	15.2	3.0
10	17.6	10.4	15.3	3.5	14.5	11.7	12.6	1.7	13.0	11.7	10.9	2.3
11	10.7	8.5	8.9	2.5	9.4	8.4	7.7	2.5	9.1	8.4	7.6	3.4
12	10.0	4.4	8.2	4.2	8.5	3.9	7.1	4.2	6.3	3.9	4.8	7.0

50 expansion intervals. The need for a high number of intervals is due to the difference in the nature of each parameter and the fact that the trend of daily values and the scale of the values for different parameters are not aligned in the historical data. The dew point temperature was the decisive parameter for 1 % and 2 %, while radiation was the decisive parameter for 5 %.

3.3. Design cooling capacities

The cooling capacities designed using the design days based on the writer's interpretation from ISO 15927-2 [22] are shown in Fig. 10. These results highlight several inconsistencies in the method's implementation and outcomes. For instance, in the BW No Shading South configuration, the cooling capacities remain almost unchanged across different risk levels (1 %, 2 %, and 5 %), contrary to expectations where stricter risk levels typically result in larger cooling capacities. Similarly, in the BW Shading East configuration, the cooling capacities show unexpected patterns, such as lower capacities for stricter risk levels than more moderate ones. This counterintuitive result indicates potential issues in how the ISO method processes climatic parameters like solar radiation and temperature for risk-based scenarios, which verifies the claims regarding the method's inconsistency. Therefore, the ISO method was excluded from the other sections of the results and conclusions.

The design cooling capacities for the chiller and sub-systems derived from simulations using ASHRAE design day input data are

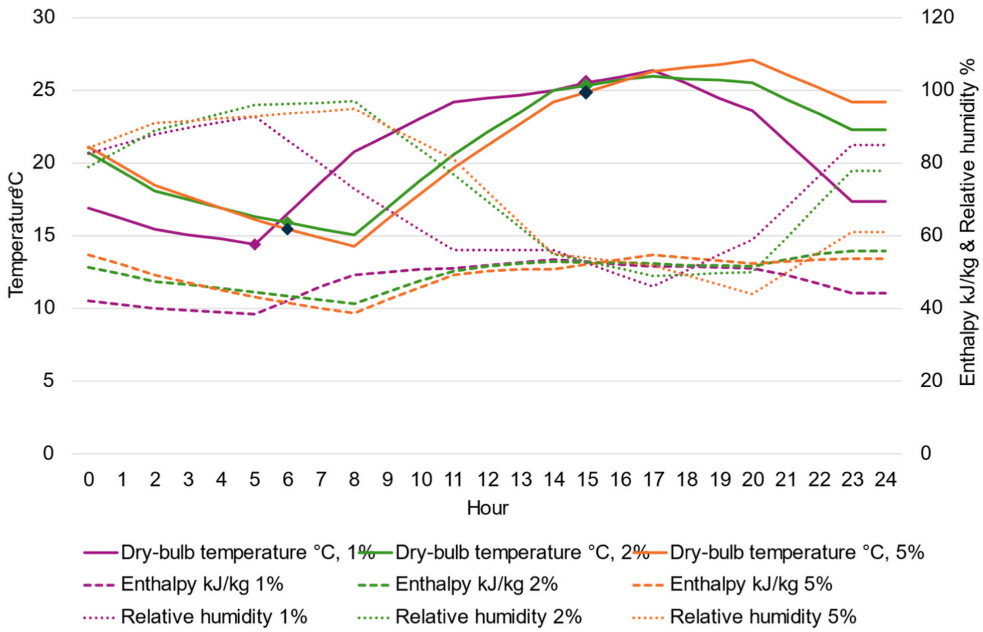

Fig. 7. July design day based on ISO 15927-2 [16].

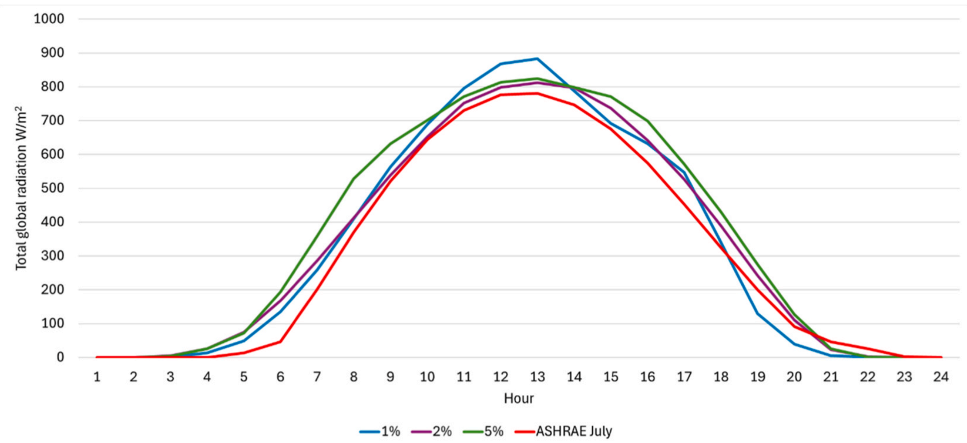

Fig. 8. July Design Day total global radiation on the horizontal surface based on ISO methods with different risk levels and calculated radiation using ASHRAE.

presented in Figs. 11 and 12. The south and east faced offices have higher capacities than the west and north faced zones. That difference is less in the Small window (SW) buildings since the windows are smaller, the capacities are relatively low in the north side rooms, and they do not get significant direct sunlight throughout the year. Fig. 11 quantifies the specific space cooling capacities per zone floor area for different risk levels and building orientations. The impact of risk level is evident, with a clear relative change in cooling capacity. For example, in south facing rooms without shading (Big Window configuration), the space cooling capacity decreases by approximately 14.3 % between the 0.4 % and 2 % risk levels (from 40 W/m^2 to 34.5 W/m^2) and further to 32 W/m^2 at 5 % risk level. A similar pattern is observed for other orientations, with East-facing rooms showing a decrease of approximately 12 % between the 0.4 % and 2 % levels and 18 % between the 0.4 % and 5 % levels. These relative changes highlight the significant influence of risk level selection on space cooling capacity.

Fig. 12 shows the total specific cooling capacities of the system components, including the AHU, space cooling, and chiller, per net floor area for each building type. The chiller capacities are consistently lower than the combined sum of AHU and space cooling

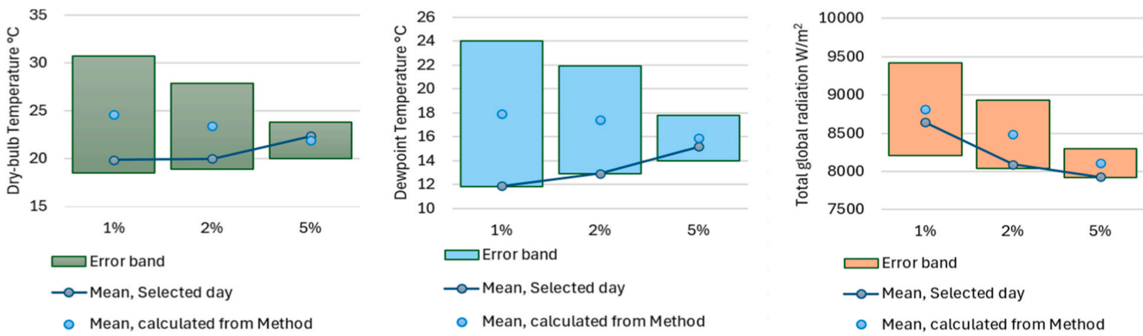

Fig. 9. Mean value of parameters for selected days for the design day of July using ISO, blue dots represent the mean based on ISO, and Error bands are based on the number of intervals needed to find one day inside the error bands for different risk levels. For readability, the error bands have different colors for different climate parameters, written in the vertical axis title.

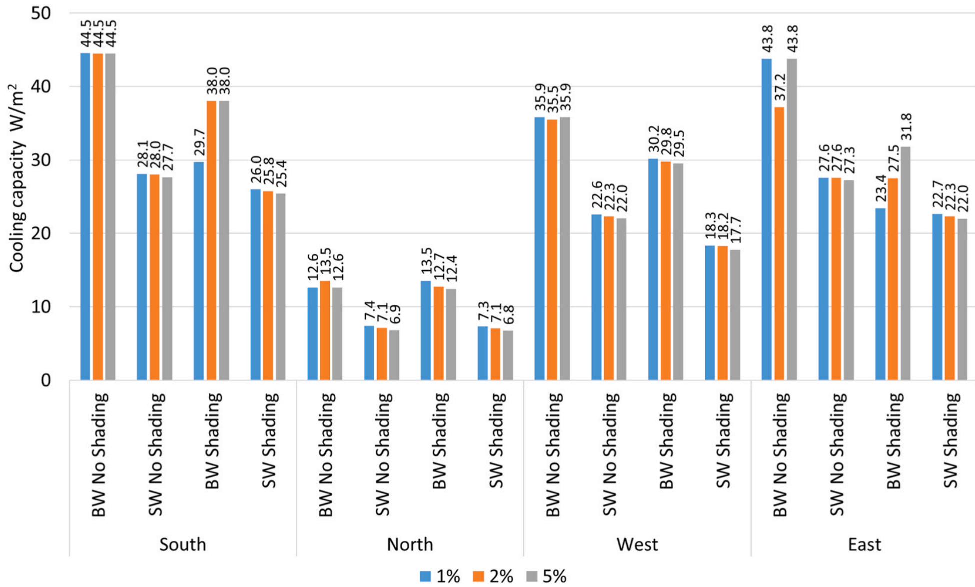

Fig. 10. Cooling capacities sized using ISO 15927-2 (16) 1 % risk level results are shown with blue, 2 % results with orange, and 5 % results with gray.

capacities due to the temporal variation in peak loads for the two systems. For instance, in the big window (BW), with no shading configurations at the 0.4 % risk level, the chiller capacity is approximately 1 % to 5 % lower than the total AHU and space cooling capacities due to the unsynchronized peak demands of both systems. A comparison scatterplot is shown in Fig. 13 using cooling capacities resulting from both methods. The deviation of capacities is as big as 25 %. Fig. 14 illustrates cooling demands by presenting a 24-h simulation result for a representative day in July for the big window no shading model, where the temporal decoupling of peak demands is highlighted as the maximum cooling power for each component does not occur simultaneously.

The AHU system maintains relatively high capacities and varies mainly between risk levels, with little difference between big or small window (BW, SW) configurations or shading conditions. This is due to the design process, which is mainly dependent on wet bulb temperature, which is constant in different scenarios and varies between risk levels according to the ASHRAE method. On the other hand, the space cooling capacities are less sensitive to the risk level selection. This substantial difference indicates the importance and dominance of radiation in sizing in the zones, while emphasizing the influence of building design and shading on AHU demand, as small window buildings consistently require less chiller capacity due to their smaller windows and better shading.

3.4. Temperature analysis

Fig. 15 shows the maximum temperature during occupied hours for each zone resulting from a simulation over 30 years period. The

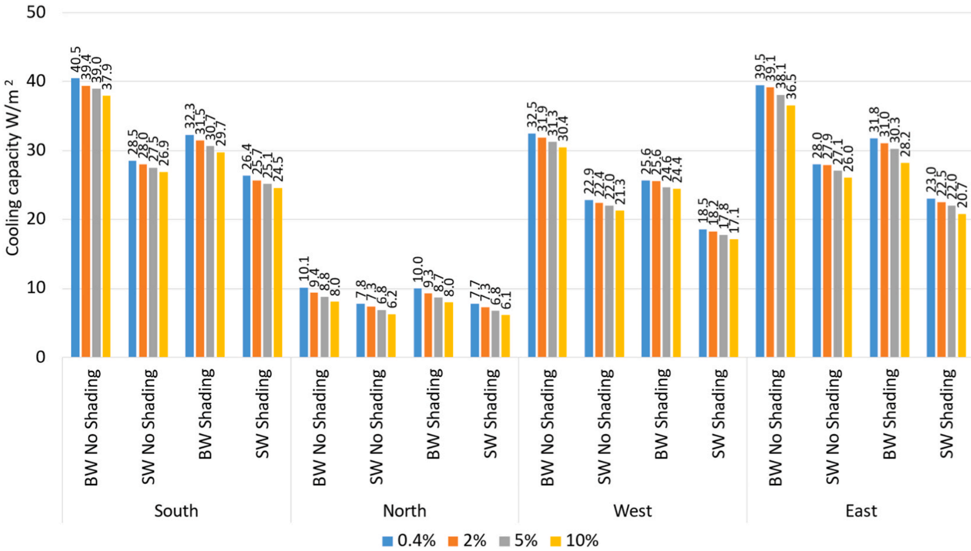

Fig. 11. Zone cooling capacities (W/m2) for every building setting and risk level using ASHRAE.

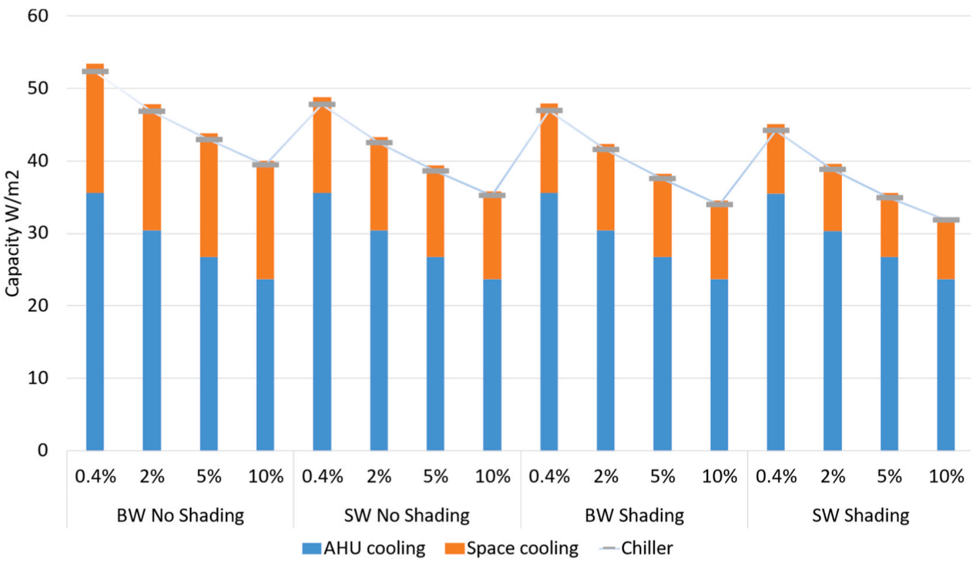

Fig. 12. Total specific cooling capacities of the cooling system components per net floor area for each building type.

north-facing offices are more sensitive considering the maximum temperature compared to other zones, where all have their maximum temperature below 25.6 °C, while north-facing zones' maximum temperatures are above 26 °C. There is not a big difference in all scenarios between big and small windows. At the same time, the stricter risk factor selection has a minor positive impact on the maximum temperature in the zones, except for the small window north zones, where the middle-risk factor (2 %) resulted in the highest maximum temperature.

Fig. 16 shows the total number of hours exceeding the 25 °C temperature threshold when cooling devices were at maximum capacity for different room orientations and building types. It is evident that no shading rooms consistently experience the highest number of exceeded hours across all directions. Exceedance differences between the no shading and shading scenarios are bigger for big window models. In contrast, the general overview of the risk factor impact on exceedances is consistent with minor differences between the results of exceeded hours, hinting at the lower importance of risk factors in the sizing process. The maximum value of the chart, if the north zone is excluded, is for a big window, no shading east office, which equals 1533 h, approximately 1.5 % of the total

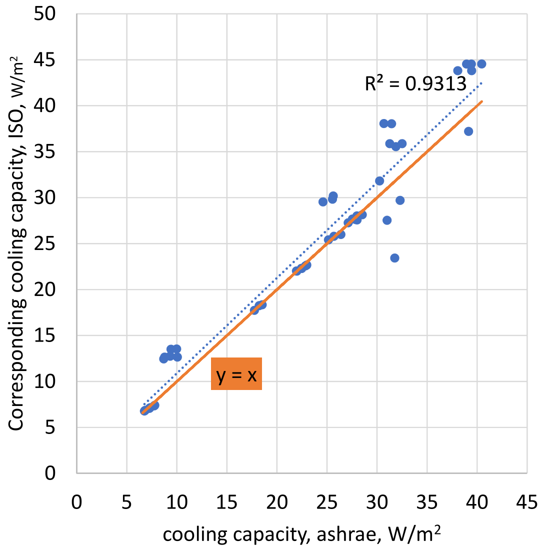

Fig. 13. A comparison scatterplot for cooling capacities corresponding to the same building model sized using both methods, showing inconsistent but generally strong correlation between the methods' results.

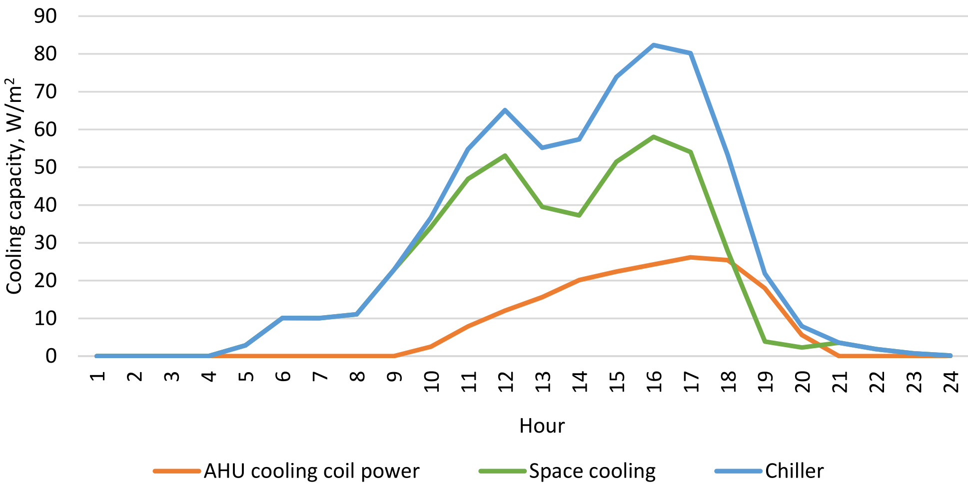

Fig. 14. AHU, Space cooling, and Chiller capacity for an example day in July, Big window no shading model.

occupied hours over the 30-year period. The provided graphs are in Fig. 17 offer a comparative overview of solar radiation data on the design day, resulting in the highest cooling capacity (the 15th of June) versus the annual radiation pattern for 2017 from long-term simulations. Both are for the north side of the building with big windows and no shading. The yearly data for 2017 reveals a shiny summer, with peak solar radiation gains from June due to indirect and diffuse sunlight typical for north-facing windows in high-latitude regions like Tartu, Estonia. The design day graph for the 15th of June demonstrates a typical summer day's radiation heat gain pattern, showing high but transient peaks in the early morning and late evening and a steady midday gain. These peaks, though less intense compared to direct sunlight on southern exposures, highlight the impact of diffuse and reflected solar radiation, especially during long summer days. The heat gains during 2017 are higher in the northern office compared to the typical design day, and years like 2017 are the main reasons for the high maximum temperature during occupied hours and the total number of exceeded hours in Figs. 15 and 16. The cooling capacity for northern zones is between 8 and 15 W/m^2, while it is more than 15 W/m^2, with an average of over 20 W/m2 for all other zones. The lower cooling capacity makes the northern zones vulnerable to temperature and radiation fluctuations, resulting in the possibility of experiencing higher temperatures. Fig. 18 indicates the maximum total exceeded hours in a 30-day period for each combination. While the north zone does not have a huge difference compared to the south and west faced zones,

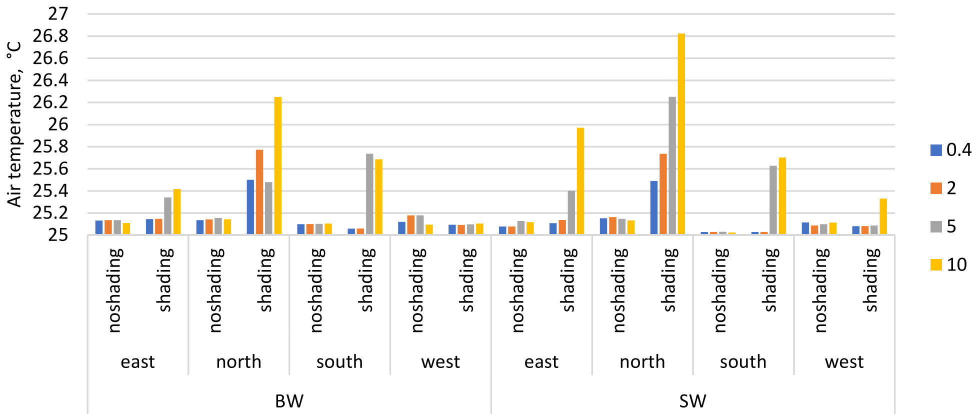

Fig. 15. Maximum temperature for each zone during occupied hours.

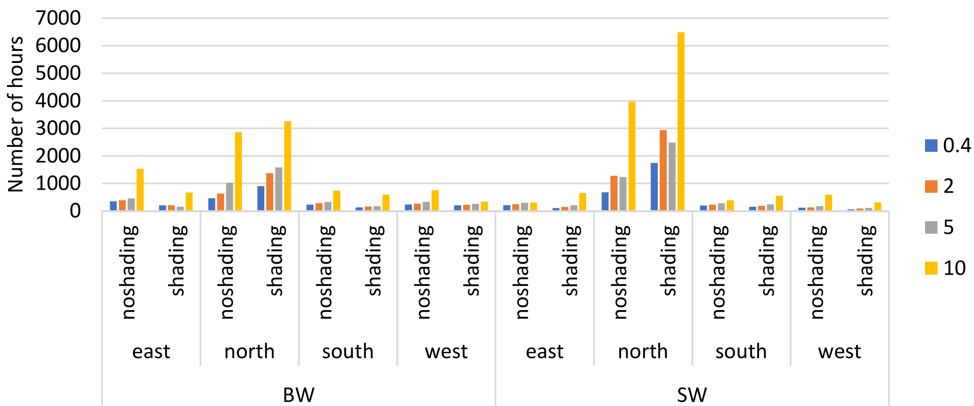

Fig. 16. The total hours when the temperature exceeded 25 °C when cooling devices were at maximum capacity in the 30 years of simulation data.

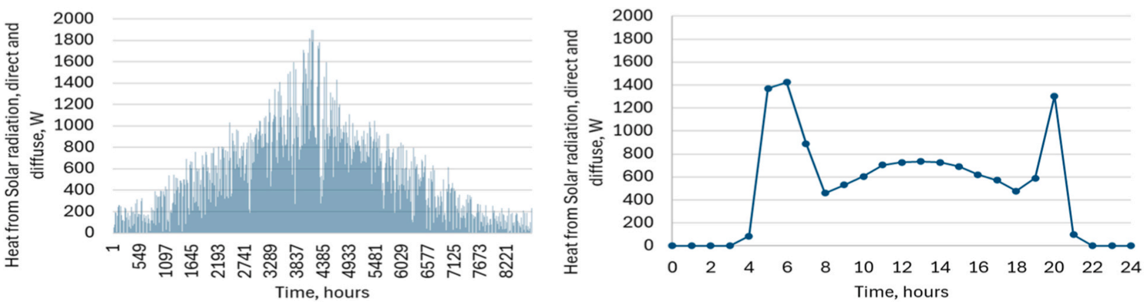

Fig. 17. Design day solar radiation heat gains (right) and yearly solar gain radiation for the year 2017 (left) for a north-facing office in Big windows, no shading building with a risk level of 0.4 %.

realizing the number of exceeded hours in long-term simulations is scattered, the east faced zone shows much lower values, reflecting that the east faced zone has a lower risk of overheating. The highest number of hours exceeding 26 °C (setpoint + 1) is lower than 3 for all zones in different directions except north-facing zones. Three hours are lower than 1 % of the total occupied hours during the 30-day period (3.6 h). This shows that following the design day generation method from ASHRAE will theoretically satisfy the TAIL method requirements in the majority of the building settings, while implementation and construction stages also have an effective role in the actual temperatures. For north-facing zones, there should be an extra effort (e.g., long-term simulation, using a rule of thumb, etc.) to

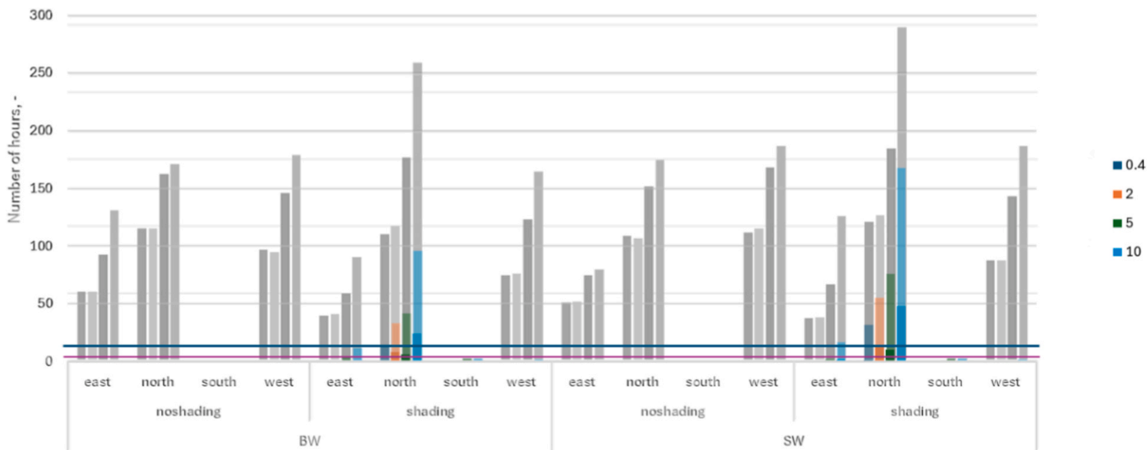

Fig. 18. Maximum total number of exceeded hours in a straight 30-day period for each combination, resulting from 30-day rolling exceedance analysis. The total number of values exceeding 26 is shown with a starker color, exceeding 25.5 is illustrated with a faded color, and exceeding 25 is illustrated with grayscale. The blue line represents the 5 % excess hour criterion [11], and the purple line shows 1 % excess hour criterion [3].

make sure the requirements will be satisfied. Another aspect visible in the results is oversizing. Except for the north-facing zone, which can be improved by smarter control strategies, the other zones show very similar excess hours for the ASHRAE [3] risk levels of 0.4, 2, and 5 %.

A comparison between AHU sizing strategies was conducted to assess the impact on indoor humidity conditions. In all models, the room unit capacities were kept constant, based on sizing with the 10 % risk level. The air handling unit cooling coil capacities, however, were varied and modeled according to the 0.4 %, 2 %, and 5 % design risk levels. The dew point distribution curve and comparison for a representative hot July month are illustrated in Fig. 19. The results indicate that under normal summer conditions, all three sizing approaches maintain similar dew point profiles. The dew point temperatures only diverge when outdoor enthalpy reaches exceptionally high levels and the AHU coil cooling capacity becomes a limiting factor. This is evident in the short periods where the 0.4 % sizing results in slightly lower dew point values, visible as downward spikes in the difference plots. The figure confirms that nearly all dew point temperatures in all three models fall below the critical 17 °C threshold, with minimal deviation, especially in the 15–17 °C range. While the 0.4 % model did reduce dew point temperature more significantly during short peak events, the difference in overall humidity control between 0.4 %, 2 %, and 5 % models remained minimal, and the total number of hours exceeding 17 °C is limited. Given that dew point temperature spikes occurred only during short periods of extreme outdoor enthalpy, and all sizing strategies maintained acceptable indoor humidity levels for the majority of the time, the findings suggest that 5 % AHU sizing is sufficient in most practical cases, even for condensing room units.

4. Discussion

Our findings regarding the EN ISO 15927-2 [22] method align closely with those reported by Pezzi et al. [14], in which they analyzed ISO 15927-2 [22] performance across multiple locations and observed counterintuitive results, where the required cooling powers for lower risk levels were sometimes higher than those for stricter conditions. Similarly, our analysis highlights inconsistencies in the ISO method's design day outputs, particularly the relative trend between solar gains and temperature, which resulted in unreliable cooling capacity estimations. Parameters like global irradiation, which have higher variability, require larger expansions of error bands compared to dry-bulb temperature, and this imbalance is addressed by a 100 times higher scale for the error band by standard (Formulas 1 and 2). This highlights the challenges in simultaneously aligning multiple parameters under a single selection process, which can result in inconsistencies, as observed with the reversed radiation trends. ISO 15927-2 [22] treats each meteorological parameter (dry-bulb, global radiation, humidity) as an independent percentile without normalization or weighting; it can produce internally inconsistent combinations that misrepresent real joint extremes. For example, the 1 % dry-bulb day may coincide with a typically low radiation, leading to under-predicted solar gains and non-monotonic sizing trends observed in the results section.

Although the ASHRAE [3] and ISO 15927-2 [22] methods have the climate file as reference and percentile calculations in common, the selection of additional climate parameters for design day selection according to ISO 15927-2 [22], together with selecting actual day data from historical data is a novel idea and has potential to further be developed and corrected, while it results in inconsistency in the current version, at least in the northern cold climate. The writers suggest that the standard be revised for the northern cold climate and have a more restrictive approach in choosing the variables, including adding weighting factors for different climate parameters. Since the parameters used in generating the design days are not of the same nature and scale, there should be a unit-less normalization approach in the process, if the error band correction is still relevant in future standard revisions.

It is likely that it is extremely difficult to identify a historical day that represented the critical outdoor conditions for all cooling

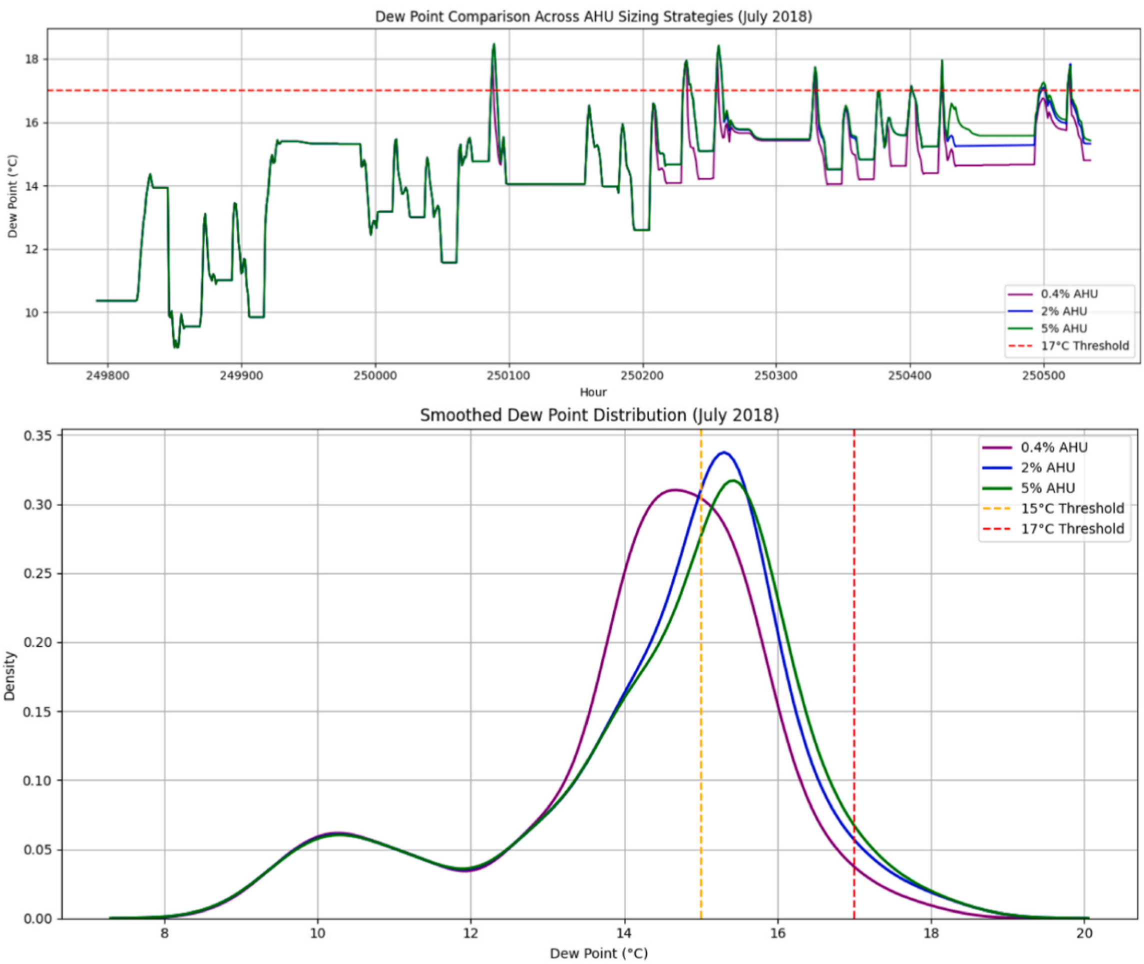

Fig. 19. The dew point distribution curve and comparison for risk level impact analysis on AHU coil size. The KDE curves in the figure help visualize the minor differences across sizing strategies.

system components – room units, AHU cooling coils, and the cooling plant, because the joint impact of different parameters is different. The ASHRAE design day generation method is probably better applicable for sizing room units and AHU cooling coils in the studied climate because they depend mostly on solar irradiance and outdoor enthalpy, respectively. However, the ASHRAE method may not capture well the probability of the simultaneous occurrence of critical values of different outdoor air parameters. Therefore, the ISO 15927-2 method has the potential to be used for sizing the cooling plant; however, further studies combined with economic feasibility analysis are needed.

New buildings have a long lifespan in the current century, so it is important to consider long-term thermal comfort assessment. Since the risk levels did not have a significant impact on thermal comfort, a 10 % risk level can be recommended to be used for the room unit sizing and 5 % risk level for AHU coil sizing. However, the operation with non-condensing room conditioning units was not specifically studied because ideal coolers used in this study correspond to high-temperature fan coils, which can contribute to dehumidification at high dew point conditions. Thus, non-condensing room conditioning units may require further analyses, which may lead to a slightly lower risk level than 5 % recommended in this study. Both risk levels result in lower outdoor temperature and enthalpy, which is the current general practice by the Estonian HVAC engineers, who use 27 °C outdoor dry-bulb temperature and relative humidity 50 % and 60 % for condensing and non-condensing room units, respectively. Therefore, despite global warming, there is no need to make the design conditions stricter, indicating that previous design values have used too high risk levels, which can be a common situation in similar climates.

Furthermore, there is an opportunity to include smart control strategies to check how they can impact thermal comfort and reduce the size of the system, consequently. This study did not explore the potential for sizing cooling systems at even lower capacities by demerging setpoints from target temperatures. In a capacity-saving approach with the target temperature of 25 °C, a more aggressive setpoint of 23 °C could be used to activate cooling more quickly and to increase the utilization of the building's thermal mass, potentially allowing for smaller room units while maintaining the same comfort range. Future studies could investigate this approach to determine its feasibility and impact on overall cooling demand by using the design days developed in this study.

5. Conclusions

This study aimed to assess the impact of varying risk levels on thermal comfort and cooling system design by implementing two standards for design day generation, ASHRAE [3] and ISO 15927-2 [22]. While ASHRAE [3] produced consistent and reliable results, the ISO method was investigated to demonstrate the potential improvements. The results demonstrate that while the selection of risk levels significantly affects system sizing, its impact on thermal comfort is less pronounced.

For space cooling, the capacities remained largely consistent across different risk levels, indicating minimal influence on thermal comfort outcomes. However, the AHU cooling capacities show substantial variation, with larger systems required at lower risk levels. Despite this increase in size, the thermal comfort assessment revealed no significant differences between risk levels. These findings suggest that sizing AHU and chiller systems at a moderate risk level of 5 % is sufficient to achieve the desired thermal comfort. Conversely, less strict risk levels, such as 10 %, are recommended for zone cooling devices, potentially supported by smart control strategies.

To further analyze AHU sizing, a comparison was conducted by keeping the room unit capacities fixed (sized at the 10 % risk level) while varying the AHU cooling coil capacity according to the 0.4 %, 2 %, and 5 % risk levels. Results showed that the dew point differences between models were minor and only emerged during brief periods of high outdoor enthalpy. Most of the time, all strategies maintained similar dew point levels, and the 95th percentile values remained below the critical threshold of 17 °C. This supports the conclusion that 5 % AHU coil sizing is sufficient under typical design conditions.

The comparison of the two standards further highlighted the limitations of ISO 15927-2 [22], which introduced inconsistencies due to its subjective parameter selection. In contrast, the ASHRAE method proved more reliable, offering consistent results across all risk levels. Based on these findings, the writers suggest that ISO 15927-2 [22] undergo a revision for northern Europe with a cold climate.

This study assessed the importance of aligning risk level selection with system design goals. While less strict risk levels can balance cost and comfort for AHU and chiller sizing, smarter control strategies are needed, specifically for north-sided zones, to ensure occupant comfort in extreme conditions or unexpected internal heat gains. Although the simulations were conducted for the Estonian climate, the findings can be applicable to other cold or temperate regions (dfb) with similar climatic conditions, such as parts of Northern Europe or North America. Future research should explore the most effective control strategies while integrating these findings with real building models and monitoring data to optimize further system performance and the process of determining design risk levels. New methods may also be developed using a combination of the ASHRAE method for generating design day values for all parameters except radiation, and integrating the ISO method for gathering radiation data for managing the issues of both methods covered in the paper.

While searching for a better method for generating design day data, future studies can conduct bigger simulations that are parametric with a focus on different variables per analysis to reflect optimization possibilities in the design.

CRediT authorship contribution statement

Seyed Shahabaldin Seyed Salehi: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Data curation, Conceptualization. **Jarek Kurnitski:** Writing – review & editing, Validation, Supervision, Funding acquisition. **Martin Thalfeldt:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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Appendix 3

III

Sepúlveda, A., Seyed Salehi, S. S., De Luca, F., and Thalfeldt, M. (2023). Solar radiation-based method for early design stages to balance daylight and thermal comfort in office buildings. *Frontiers of Architectural Research*, 12(6), 1245–1264. https://doi.org/10.1016/j.foar.2023.07.001

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RESEARCH ARTICLE

Solar radiation-based method for early design stages to balance daylight and thermal comfort in office buildings

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Solar access;
Daylight;
View out;
Window sizing

Abstract There is a lack of facade design methods for early design stages to balance thermal comfort and daylight provision that consider the obstruction angle as an independent variable without using modeling and simulations. This paper aims to develop easy-to use solar radiation-based prediction method for the design of office building facades (i.e., design parameters: room size, window-to-floor ratio, and glazing thermal/optical properties) located in urban canyons to balance daylight provision according to the European standard EN 17037:2018 and thermal comfort through specific cooling capacity. We used a simulation-based methodology that includes correlation analyses between building performance metrics and design parameters, the development of design workflows, accuracy analysis, and validation through the application of the workflows to a new development office building facades located in Tallinn, Estonia. The validation showed that the mean percentage of right/conservative predictions of thermal comfort classes is 98.8% whereas for daylight provision, it is higher than 75.6%. The use of the proposed prediction method can help designers to work more efficiently during early design stages and to obtain optimal performative solutions in much shorter time: window sizing in 73,152 room combinations in 80 s.

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1. Introduction

The building sector is one of the main reasons of global warming as it is responsible for 30% of the total Greenhouse Gas emissions (Wei et al., 2018). Moreover, buildings' energy needs account for 40% of the total energy consumed in Europe (Ahmad et al., 2014). Indeed, the Member States are encouraged by the Energy Performance of Buildings Directive 2010/31/EU (EPBD) to define specific requirements for new buildings (starting from January 1, 2021) to become nearly zero-energy buildings (nZEBs) (European Commission, 2010). In consideration of occupants visual comfort, the European standard EN 17037:2018 "Daylight in buildings" defined methods to quantify the level of different daylight aspects: sunlight exposure or solar access, view out, daylight provision, and glare protection (European Commission, 2018). Daylight provision has been proven crucial to balance humans' circadian rhythm (Duffy and Czeisler, 2009; Lockley, 2009). Indeed, daylight is the most preferred light source by building occupants (Knoop et al., 2019). During the COVID-19 pandemic, building occupants became more aware about how daylight in indoor spaces (considered as one environmental factor related to visual quality) can influence their psychological and physical well-being (Batool et al., 2021). Nowadays, facades with high window-to-wall ratios (*WWR*s) are a common solution at northern latitudes due to the lack of sun hours during the winter and the importance of the view to the outside (Thalfeldt et al., 2013). Nevertheless, the excess of daylight, for instance, caused by the presence of direct sunlight (despite of its importance on human health (Samuels, 1990)) can provoke summer thermal discomfort (Simson, 2019) and visual glare discomfort which is a complex phenomenon that depends on several factors such as the viewing direction, view position, luminance distribution and contrast, weather conditions, and external obstructions (Osterhaus, 2005). Indeed, relationship was observed between lighting level satisfaction and perceived thermal comfort, whereas the overall comfort depends more on thermal conditions than the lighting level (Fakhari et al., 2021). In addition, the balance between energy consumption and visual comfort in highly glazed buildings with adaptive biomimetic facades was proved feasible (Sheikh and Asghar, 2019). Facade design in urban canyons, which are characterized by homogeneous high obstruction levels, are challenging for architects and designers: the fulfillment of daylight provision requirements in high-obstructed lower floors and the minimization of cooling capacity (directly related to the draught risk) of low-obstructed higher floors are difficult to obtain with the same design parameters. Thus, floor dependent facade design decisions in the early design stages are needed to meet both, daylight and thermal comfort requirements while avoiding additional costs required by future renovations (Sepúlveda, 2022).

1.1. Balancing energy performance and daylight in buildings

The proposal of facades Multi-objective simulation methods were commonly used in previous investigations to achieve efficient building/facade level design decisions: Chen et al. (Pilechiha et al., 2020) found that the use of an efficient cooling system has the potential to achieve better trade-offs between energy performance and daylight provision in offices located in Singapore, and Konis et al. (2016) achieved the simultaneous increase of daylight provision (27%–65%) and decrease of Energy Use Intensity (EUI) (4%–17%) depending on the climate (Helsinki, New York, Los Angeles, Mexico city) by using its proposed Passive Performance Optimization Framework (PPOF).

Other studies used standard simulation methods based on validated softwares (EnergyPlus, DAYSIM, E-Quest) to propose efficient design decisions to balance energy and daylight during the facade design phase of different type of buildings located in low latitudes (25.762°–34.052°) (Li et al., 2016; Shen and Tzempelikos, 2012; Shishegar and Boubekri, 2017). Shen and Tzempelikos (2012) proved on one hand, that visible transmittance higher than 50% have the ability to allow enough daylight provision for *WWR*s higher than 50%, on the other hand, *WWR*s between 30% and 50% can result in lower energy consumption. Li et al. (2016) found that Building Integrated Solar Thermal Shading (BISTS) can effectively improve daylight provision in single perimeter office room by increasing the Useful Daylight Illuminance level (i.e., between 100 lux and 2000 lux) while achieving a 5.3% reduction of the primary energy use. Shishegar and Boubekri (2017) found that, for hot and arid climates, a *WWR* of 40% provides the highest electrical energy savings almost independently of artificial lighting control.

Regarding studies that considered multi-objective optimization (MOO) methods, Pilechiha et al. (2020) showed that their framework (to select room/window dimensions) could improve daylight provision and view out for more than 80% of the utilized south-oriented office room area while decreasing EUI about 12%. In addition, Naji et al. (2021) who proposed and used a MOO method to minimize thermal/visual discomfort and life cycle costs (LCC) of residential buildings located in the Australian context, found that the optimal solutions were unique for each climate zone: 27%–31% of energy savings and 6%–55% reduction of thermal comfort discomfort hours (compared to the baseline).

Several investigations proposed rules of thumb for facade design for different building types located at high latitudes (De Luca et al., 2022; Thalfeldt et al., 2013; Vanhoutteghem et al., 2015). Vanhoutteghem et al. (2015) highlighted the difficulties to achieve a good balance between daylight provision, energy consumption, and overheating protection in nZEB Danish single-family homes: low g-values and high visible transmittance values were recommended for south-oriented rooms and high g-values for north-facing windows to reduce the heating demand. Within the Estonian context, the optimal energy performance, costs and daylight are related to office buildings with highly transparent triple glazing systems (*WWR* of 40%) (Thalfeldt et al., 2013). De Luca et al. (2022) found through parametric analyses that static shadings can reduce visual discomfort by up to 89.8%, primary energy use by up to 29.1%, and provide adequate levels of daylight and view out for two existing NE/SE-oriented classrooms located in Tallinn, Estonia.

1.2. Design recommendations for Estonian offices

Currently in Estonia, there is a local standard EVS-EN 17037:2019+A1:2021 (Estonian Centre for Standardisation and Accreditation (Non-Profit Association), 2022) in line with the EN 17037:2018 (European Commission, 2018) (based on minimum Daylight Factor (min*DF*) and Spatial Daylight Autonomy (*sDA*) metrics). A recent investigation proved the reliability of the EN 17037:2018 (i.e., method 1: min*DF* criterion), through the comparison with the well-stablished method LM-83-12 based on the *sDA* metric (Illuminating Engineering SocietyThe Daylight Metric Committee, 2013), against the Estonian standard EVS 894:2008/A2:2015 (Sepúlveda et al., 2020). Regarding energy efficiency in buildings, Estonia has clear regulations that define the concept of Nearly Energy Zero Buildings (NZEB), assessment methodologies, and requirements based on the primary energy (Estonian Government, 2012, 2015).

Typically, office buildings in Estonia have active cooling systems because it is normally not possible to protect against overheating risk during the warm season only with hybrid (i.e., mechanical and natural) ventilation (Simson, 2019) due to the high level of internal gains that must be considered according to the Estonian regulation (Estonian Government, 2015), and to the possible solar gains. Therefore, a wrong combination of *WWR*, room dimensions, glazing type (visible transmittance: Tvis and total solar energy transmittance: g-value) and orientation/external obstructions of the office room could be detrimental not only for the energy performance (Thalfeldt, 2016), but also for the daylight provision (Sepúlveda et al., 2022a). For instance, Pikas et al. (Kurnitski et al., 2013) found that photovoltaic panels to generate electricity in Estonian office building would be necessary to achieve NZEB requirements despite of not being a cost optimal solution in 2014. In Estonian office buildings, which are typically very well insulated, the main factors of influence of the cooling capacity were the internal and solar heat gains due to the small differences between cooling set point and outdoor temperature (Seyed Salehi et al., 2021). Moreover, the higher solar heat gains related to high incident solar radiation levels are normally caused by low sun altitudes and sunny days (e.g., during spring/autumn) leading to an increase of the building's cooling capacity to maintain indoor set points. Higher air velocity (required to reach higher cooling capacity) in occupied zone is easily perceived as draught, which causes occupant dissatisfaction and complaints, as well as decrease in the productivity or effectively useable floor space area (Kiil et al., 2019). In fact, Kiil et al. (2020) demonstrated that high *WWR*s result in higher cooling loads and increase the need for larger room cooling units, higher cooled airflow rates or lower supply air temperatures to achieve a cooling set point, the latter factors also increasing the risk of draught in occupied office spaces.

1.3. Novelty and objectives of this investigation

In 2005, Li et al. (2005) applied regression analyses to predict the increment of cooling energy in an office room located in Hong Kong, China from the incident solar radiation and *WWR*·Tvis (common design parameter in early design stages). However, this prediction method does not consider different g-values of the glazing system or obstruction angles of the surrounding buildings, which can have a crucial impact on the predicted cooling energy increment. Although previous investigations proposed optimization workflows (Chen et al., 2018; Huang et al., 2021; Konis et al., 2016; Pilechiha et al., 2020) and rules of thumb (De Luca et al., 2022; Thalfeldt et al., 2013; Vanhoutteghem et al., 2015) to balance energy performance and daylight in buildings during early design stages, there is a lack of: (1) consideration of the obstruction angle as independent variable; and (2) the simulation-free prediction methods to design office buildings with a desired thermal comfort level (affected by the specific cooling capacity *SCC*). Thus, the consideration of different obstruction angles is important to propose easy-to-use prediction methods for architects and designers to design office buildings located in urban canyons. Thus, there is a need to understand correlation between obstruction angle and incident solar radiation/daylight provision/cooling capacity for different facade orientations (e.g., South: S, South-east: SE, East: E, North-east: NE, North: N, North-west: NW, West: W, South-west: SW) to balance daylight and thermal comfort in office buildings, especially in cold climates where there is a poor daylight availability during the cold season, and high thermal mass constructions. In order to fill this research gap, the main aim of this investigation is to develop an easy-to use solar radiation-based prediction method for the design of office buildings facades (i.e., decisions: room size, window-to-floor ratio: *WFR*, Tvis, g-value) located in urban canyons to balance daylight provision according to the EN 17037:2018 and thermal comfort. Firstly, the scientific novelty of this investigation lays on the correlation study between the mentioned design variables and building performances (*sDA* and *SCC*). Secondly, the development of prediction methods can help architects and designers to work more efficiently during early design stages and to obtain more performative solutions in shorter time. To fulfill the aims of the study, the objectives of this investigation are as follows:

- O1: To develop a solar radiation-based prediction method for *WFR*·Tvis based on obstruction angle-incident solar radiation to fulfill daylight provision according to method 2 defined by the EN 17037:2018;
- O2: To develop a solar radiation-based prediction method for *WFR*·g-values based on obstruction angle-incident solar radiation to ensure a certain level of thermal comfort through controlling *SCC*;
- O3: To propose design workflows based solar radiation-based prediction methods for the early stage design of facades in future office buildings in Estonia;
- O4: To validate the proposed design workflow through its application to design an office-building facade initial solutions in Tallinn, Estonia.

2. Methodology

In order to achieve the objectives of this investigation (O1—O4), we used a simulation-based approach (Fig. 1):

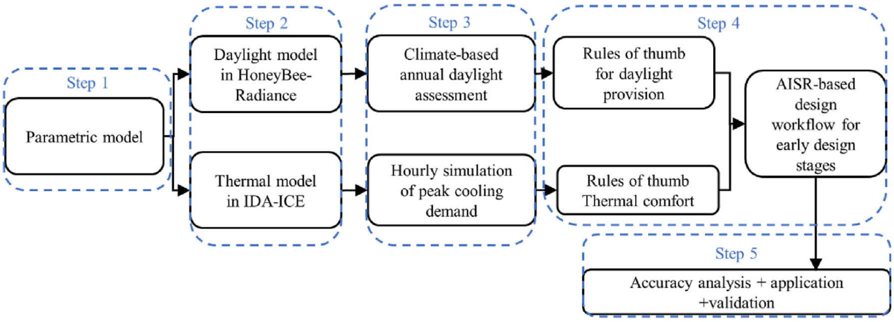

Fig. 1 Flowchart of the methodology used in this investigation.

1) Creation of the parametric model of a generic office room (Section 2.1);
2) Set up daylight (Section 2.2) and thermal (Section 2.3) parametric models including different visible transmittances (Tvis) and g-values related to different glazing types;
3) Annual assessment of daylight provision according to method 2 proposed in the EN 17037:2018 (Section 3) and *SCC* (Section 4);
4) Analysis of the annual assessment results to generate easy-to-use rules of thumb to balance daylight provision (O1, Section 3.1) and thermal comfort (O2, Section 3.2);
5) The application and validation of the proposed solar radiation-based workflow (O3) to balance daylight and thermal comfort in a new office building development project within Estonia (Section 3.3–3.5).

2.1. Parametric model of a generic single office

We used a simulation-based methodology with a single-zone approach for the assessment of daylight provision and *SCC*. Thus, we built a parametric model of a generic office room in GH for Rhinoceros. The range for all the design parameters considered in the parametric model can be seen in Fig. 2. The independent variables or design parameters of the parametric model are: room orientation (*ro*), room width (*rw*), room depth (*rd*), window width (*ww*), window height (*wh*), and obstruction angle (θ). The dependent variables are *sDA* (%) and *SCC* (W/m^2).

Since the case studies are located in Tallinn, Estonia (Lat. 59°26′N, Lon. 24°45′E, humid continental climate according to Köppen-Geiger classification DFb (Peel et al., 2007)), we used a building typology already used in previous investigation within the Estonian context (Sepúlveda et al., 2020, 2022a). The room dimensions (*rw*: 3.5–6.5 m, *rd*: 3.5–7.5 m, room height: 3 m) and number of orientations were selected to obtain a representative sample of typical office rooms in Estonia. The small 3.5 m × 3.5 m rooms represent a single office of approximately 12 m^2. Room areas of 20–40 m^2 represent medium-size offices. Rooms with a size of 6.5 m × 7.5 m represent large offices of ∼50 m^2. The total number of room combinations is 61,440 for *sDA* and *SCC* simulations.

We set the maximum width of 1.75 m for a single glazed area. Thus, the number of vertical window dividers was varied from 0 (*ww* = 1.75 m) to 3 (*ww* = 5.655 m) (Fig. 3 (a)). The frame width (4.3–6.6 cm) was calculated to ensure a constant frame ratio of 12% (Fig. 3 (a) and (b)). In Fig. 3 (c), different room combinations have the same

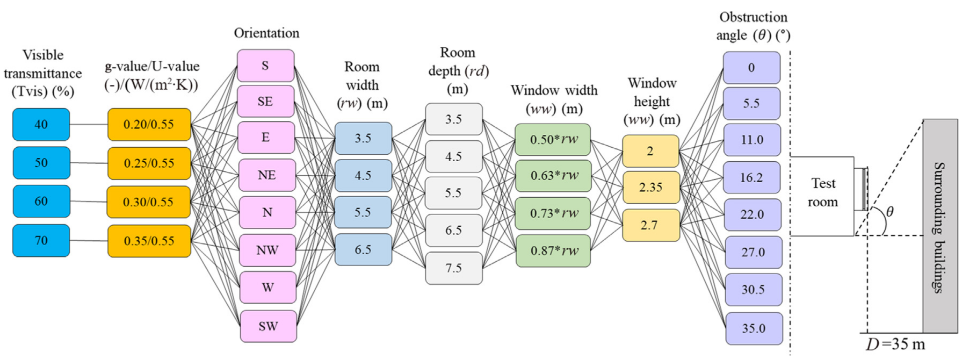

Fig. 2 Diagram of room parameter combinations and representation of the obstruction angle θ for a generic room. An obstruction angle is considered null ($\theta = 0°$) when the roof of the surrounding building/external obstruction is at the same level or below the floor level of the test room.

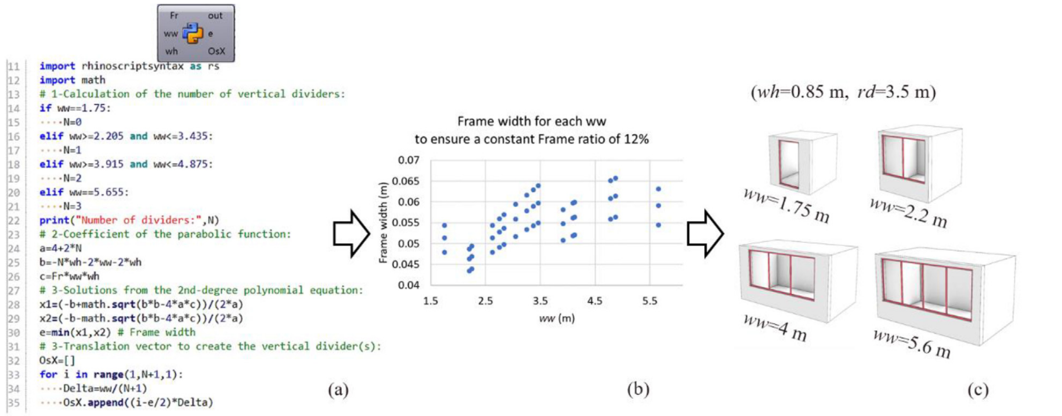

Fig. 3 Algorithm to calculate the frame width (*e*) to ensure a specific frame ratio (*Fr*) of 12% depending on the window width (*ww*). (a) Frame width-*ww* combinations for the generated room combinations; (b) Room combinations with different *ww* values and constant window bottom-sill height (*wh*) of 0.85 m; (c) Delta (distance) between vertical dividers and OsX (ranslation vector) to generate each window frame divider.

frame ratio despite of the different *ww* and number of dividers to ensure the structural feasibility of the fenestration system. The window top-ceiling distance was fixed to 0.15 m and the window heights were 2 m, 2.35 m, and 2.7 m corresponding to a windowsill height of 0.85 m, 0.5 m, and 0.15 m, respectively. Thus, considering all the room and window sizes, *WFR* varied from 13.3% to 67.1%.

The distance between the external facade of the test room and the surrounding building was set to 35 m, which represents the worst-case scenario for daylight provision (for the same obstruction angle), i.e., minimum availability of diffuse (from the sky) and reflected light to the indoor space due to closer luminance sources (light reflected by the surrounding buildings). In order to model an urban canyon, the opposite building was modelled as continuous facade and the height was varied to simulate the mean obstruction angle (θ) from 0° to 35.0° (Fig. 2) as considered in previous research (Sepúlveda et al., 2022a). As triple glazing systems are a common and cost-optimal design solution within the Estonian context, we considered a fixed total thermal transmittance (U-value) of 0.55 W/(m^2·K) (Thalfeldt et al., 2013, 2017). The visible transmittance of the glazing system was varied from 40% to 70%. The g-values were varied from 0.20 to 0.35 (Fig. 2) to consider triple-glazing systems in the market with a Tvis-g-value ratio of 2 (LSG = 2) (Lee et al., 2022), maximizing the potential balance between daylight provision and *SCC* in all the generated rooms (Sepúlveda et al., 2022a). Finally, we did not consider shading systems in our parametric model because they can be considered in later stages of facade design only (cost-efficiency) if predicted size of glazed areas required to fulfill daylight requirements is larger than maximum size of glazed areas required to control *SCC*.

2.2. Daylight provision assessment

In early design stages the consideration of daylight is more suitable than glare protection as stated by Sepúlveda (2022): glare protection issues and further tuning of window properties and shading should be solved during the next design stages. For each generated room combination we assessed daylight provision according to method 2 defined by the EN 17037:2018: based on *sDA* (European Commission, 2018). The reference plane was located at 0.85 m from the room floor level as defined by the EN 17037:2018. In addition, as recommended by the standard 0.5 m × 0.5 m grid cells were considered for the calculation of horizontal illuminance values. The offset distance between the grid points and the room walls was 0.5 m in order to avoid unrealistic low illuminance values due to the common presence of furniture close to the interior walls. The reflectance values of the window frame were set to 0.5 corresponding to a silver aluminum window frame and the reflectance values of the opaque surfaces were set according to standard values defined in the EN 17037:2018 (Table 1).

According to method 2, a minimum, medium, and high level of recommendations for daylight provision correspond to the simultaneous fulfillment of $sDA_{100,50}\geq95\%$ and $sDA_{300,50}\geq50\%$, $sDA_{300,50}\geq95\%$ and $sDA_{500,50}\geq50\%$, and $sDA_{500,50}\geq95\%$ and $sDA_{750,50}\geq50\%$, respectively (Table 2). As for annual climate-based daylight simulations such as the

Table 1 Reflectance (*R*) values for opaque surfaces recommended by the EN17037 for daylight simulations (European Commission, 2018).

Surface	Reflectance (0–1)	Surface	Reflectance (0–1)
Interior walls	0.5	External ground	0.2
Floor	0.2	External facade and buildings	0.3
Ceiling	0.7		

DA simulations, we used the matrix-based method called "2-phase method" implemented in the component "HB Annual Daylight", which has been proved reliable for annual daylighting calculations with conventional fenestration systems such as the glazing we have in our daylight models (Subramaniam, 2017). Thus, we used the Radiance parameters show in Table 3 (Sepúlveda et al., 2022b).

2.3. Thermal comfort assessment

The Estonian regulations set the summer-time over-heating requirements for new buildings and their fulfillment is the prerequisite for not installing a mechanical cooling system (Riigi Teataja, 2020). The requirements stipulate the maximum number of degree-hours in critical rooms of a building over limit temperature, which for residential and non-residential buildings are 27 °C and 150 °Ch, 25 °C and 100 °Ch, respectively. Rules of thumb for fulfilling both daylight and over-heating requirements in apartment buildings were developed by Sepúlveda et al. (2020). However, the limit temperature 25 °C and the degree-hour threshold 100 °Ch in non-residential buildings are significantly stricter than in residential buildings. Additionally, the internal gains in non-residential buildings are larger than residential buildings, which in practice obligates controlling the room temperatures by installation of mechanical cooling systems.

Assuring thermal comfort in ventilated spaces requires controlling both the room temperature and air velocity to diminish complaints (Fanger and Christensen, 1986) and too high air velocities are in practice often the cause for complaints even when the air temperature is within required limits (Hens, 2009; Kähkönen, 1991). Typically, cooling panels, thermally activated buildings systems (TABS), active chilled beams and fan-coil units are used for room cooling in Estonia. Kiil et al. (2020) conducted a thorough field-study of air temperature and air velocities in office buildings during cooling season where each of these systems were installed. They concluded that in buildings with radiant cooling panels, TABS and active chilled beams indoor climate category remained in between I (high level) and II (medium level), whereas the building with fan-coils and largest *SCC* performed worst and the indoor climate category III (minimum level) was reached. Additionally, the building with cooling panels and lowest *SCC* performed best and indoor climate category I was reached in most rooms. Although, good indoor environment requires careful design and proper installation of mechanical cooling, the prerequisite of assuring thermal comfort is well controlled *SCC*.

Table 3 Radiance parameters used for annual daylight simulations in HoneyBee-Radiance (Sepúlveda et al., 2022b).

Radiance parameter	Value
Ambient bounces (*-ab*)	6
Ambient divisions (*-ad*)	25,000
Ambient super-samples (*-as*)	4096
Sampling (*-c*)	1
Direct certainty (*-dc*)	0.75
Direct pretest density (*-dp*)	512
Specular threshold (*-st*)	0.15
Direct relays (*-dr*)	3
Source substructuring (*-ds*)	0.05
Direct thresholding (*-dt*)	0.15
Limit reflection (*-lr*)	8
Limit weight (*-lw*)	4e-07
Specular sampling (*-ss*)	1.0

Therefore, in this study the recommended thermal comfort levels are defined through *SCC*.

The best performing currently available common cooling system is with radiant cooling panels, but since there is no forced convective air flow in these systems, their cooling capacity is limited. Võsa et al. (Karl-Villem et al., 2022) measured the performance of cooling panels and Salehi et al. (2022) validated the thermal model and concluded that the real nominal cooling output of the panels k_c corresponded well with the values provided in the technical documentation. The maximum *SCC* cooling capacity of radiant cooling panels can be calculated based on the parameters of cooling panels (Zehnder Baltics OÜ, 2018) and typical design parameters of cooling systems as follows:

$$\Phi_{\text{specific,max}} = CP_{\text{area,specific,max}} \cdot k_{\text{c,specific}} \cdot \left(\frac{t_{\text{ret}} - t_{\text{sup}}}{\ln\left(\frac{t_{\text{sup}} - t_a}{t_{\text{ret}} - t_a}\right)} \right)$$

where $\Phi_{\text{specific,max}}$ is the maximum *SCC* (W/m^2), $CP_{\text{area,specific,max}}$ is the maximum cooling panel area per room floor area (0.5), $k_{\text{c,specific}}$ is nominal cooling output per panel area (9.98 W/K/m^2), t_{ret} is design return temperature of cooling system (18 °C), t_{sup} is design supply temperature of cooling system (15 °C) and t_a is design room temperature for cooling (25 °C). The resulting maximum *SCC* with cooling panels is thus 39.9 W/m^2. As Kiil et al. (2020) showed, the active chilled beams are a suitable cooling solution for

Table 2 Recommendations of daylight provision by daylight vertical openings according to the EN 17037:2018 (European Commission, 2018).

Level of recommendation	Target illuminance E_T (lux)	Fraction of space for target level $F_{\text{plane, \%}}$ (%)	Minimum target illuminance E_{TM} (lux)/DF (%)	Fraction of space for minimum level $F_{\text{plane, \%}}$ (%)	Fraction of daylight hours, $F_{\text{time, \%}}$ (%)
Minimum	300	50	100	95	50
Medium	500	50	300	95	50
High	750	50	500	95	50

assuring indoor climate category II and REHVA Guidebook No. 5 (Virta et al., 2007) suggested optimal *SCC* between 60 and 80 W/m^2 for active chilled beams. Based on the presented information, the *SCC* limits for different comfort levels used in this study are the following: minimum, medium, and high for a maximum *SCC* of 80, 60, and 40 W/m^2, respectively.

2.4. Thermal model

The thickness of interior walls and ceilings were constant and construction materials thermal properties were adjusted (Domínguez-Muñoz et al., 2010) to achieve thermal performance related to heavy construction type used in previous research (Seyed Salehi et al., 2021) (Table 4). The window constructions with a constant LSG ratio of 2 are shown in Table 5.

Slab floor and interior walls were considered as adiabatic surfaces as it is a typical boundary condition for office rooms energy simulations. However, we considered heat transfer through the exterior wall and solar exposure and the thermal mass of the interior surfaces was accounted for in the simulations. Required usage profiles for internal gains in office buildings (same for occupancy, lighting, and equipment) by Estonian regulations can be seen in Fig. 4. For a single office, the area per person is 10.0 m^2 and the mean level of activity is 1.2 met (Table 6). HVAC settings used in our thermal model are displayed in Table 6. Ideal coolers controlled with proportional-integral (PI) controllers were used as room units to model the cooling capacities. Mechanical ventilation was also considered: minimum fresh air of 1.4 L/sm^2 during occupied hours (CEN, 2019). Additionally, the ventilation airflow rate of a non-residential building is deemed to be 0.15 L/sm^2 during unoccupied hours. Although dimming control has been more used in new Estonian office buildings during the past years, peak cooling load for sizing cooling room units was calculated in this study and typical ON/OFF control with predefined schedule was assumed in these calculations for a safety margin. It cannot be assured that the occupant does not draw interior blinds when peak cooling load occurs and thus, it triggers the operation of the lighting system on full power. As the focus of this study is on early-stage design and many rough estimations need to be done, smart controls for lighting system and blinds can be used to reduce peak cooling loads in latter design stages if needed to simultaneously reach high daylight and thermal comfort levels.

Table 5 Windows glazing specifications.

Parameter	Type 1	Type 2	Type 3	Type 4
Solar heat gain coef. (SHGC) (0–1)	0.2	0.25	0.3	0.35
T. Solar transmittance (0–1)	0.17	0.21	0.25	0.3
Visible transmittance, Tvis (%)	40	50	60	70

Note: Internal emissivity = External emissivity = 0.9, Glazing U-value = 0.55 W/(m^2·K).

3. Results and discussion

3.1. Minimum *WFR*·Tvis to ensure a specific daylight provision class

The aim of this section is to develop a solar radiation-based prediction method for minimum *WFR*·Tvis depending on annual incident solar radiation (AISR) related to the external facade of the office room to fulfill different levels of daylight provision according to the method 2 defined by the EN 17307:2018. We define the metric minimum *WFR*·Tvis (min*WFR*·Tvis) as the main design variable to achieve a certain level of daylight provision, since it includes all the design parameters affecting daylight provision. As can be seen in Fig. 5, the level of obstruction can be correlated to the AISR that the center of the external facade receives during the whole annual period (as considered for $sDA_{x,50}$ calculations), which represents an useful design input for the designer during the building massing stage (Sepúlveda and De luca, 2020).

In Fig. 6, the linear correlation coefficient R^2 for different AISR values, room orientation, and illuminance threshold *x* is shown. Since there is not strong correlation

Table 4 Thermal properties of the building envelope.

Element	Construction	Total Thermal transmittance (W/(m^2·K))	Layer density (kg/m^3)	Layer Specific Heat (J/(kg·K))	Layer Thermal conductivity (W/(m·K))
External wall	Render 10 mm	0.128	1800	790	0.8
	Concrete 150 mm		2300	880	1.7
	Expanded Polys. 270 mm		20	750	0.036
	Concrete 50 mm		2300	880	1.7
Slabs	Floor coating 5 mm	0.2	1100	920	0.18
	Concrete slab 150 mm		2300	880	1.7
	Insulation 245 mm		92	2010	0.052
Internal walls	Concrete 150 mm	3.8	2300	880	1.7
Window frame	Aluminium 50 mm	2	450	900	0.1

Note: Polys.—Polystyrene.

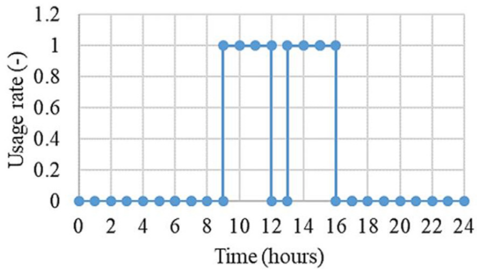

Fig. 4 Usage profiles of occupancy, lighting, and equipment for a single office in Estonia (Estonian Government, 2015).

($R^2 < 0.90$) between $sDA_{x,50}$ and AISR for almost all the illuminance thresholds (100 lx, 300 lx, and 500 lx), $sDA_{100\text{-}500,50}$ cannot be predicted with linear fitting. Therefore, the development of $sDA_{100-500,50}$ prediction formulas are not viable in terms of accuracy as the min*DF*-based one developed by Sepúlveda et al. (2022a).

Moreover, designers might prefer to work with simple solar radiation-based prediction methods to achieve a certain level of recommendation according to the EN 17037:2018. Specifically, for each *WFR*·Tvis, the minimum $sDA_{x,50}$ is searched (orange circles in Fig. 7 related to the most conservative daylight level for each *WFR*·Tvis) in order to ensure the fulfillment of a desired level of daylight provision based on $sDA_{x,50}$ thresholds (Table 2). Then, the min*WFR*·Tvis_{50} and min*WFR*·Tvis_{95} is the minimum *WFR*·Tvis, for which minimum $sDA_{x,50}$ is higher than 50% (red dotted lines represent the threshold for target level) and 95% (green dotted lines represent the threshold for minimum target level), respectively (Fig. 7).

Recommendations for min*WFR*·Tvis_{50} and min*WFR*·Tvis_{95} can be made for different illuminance thresholds (i.e., *x* values) (Fig. 8(a) and (b)). Moreover, considering the definition of daylight provision classes defined in Table 2 and the min*WFR*·$\text{Tvis}_{50\text{-}95}$ values, the solar radiation-based prediction method for daylight provision can be represented graphically (e.g., for south-oriented rooms, see Fig. 8(c)). According to this prediction method to achieve a minimum level of daylight provision (Fig. 9(a)), the min*WFR*·Tvis recommended value for any orientation is between 0.1 and 0.25 for θ between 0° and 35°, respectively. For a medium level of recommendation (Fig. 9(b)), the min*WFR*·Tvis value for any orientation should be between 0.225 and 0.4 for θ between 0° and 35°, respectively.

Table 6 Internal gain parameters for Estonian single office.

Parameter	Value
People density	0.1 p/m^2
Metabolic Rate	1.2 met
Equipment power density	12 W/m^2
Lighting power density	6 W/m^2
Lighting control	ON/OFF
Target Illuminance	500 lux

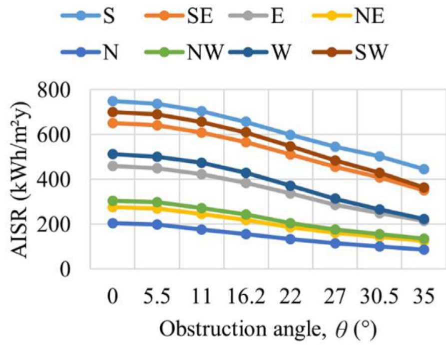

Fig. 5 Accumulated AISR for different room orientations and obstruction angles. AISR values were calculated in a 1 m × 1 m surface located at the center of the external facade of the room.

Finally, to achieve a high level of recommendation (Fig. 9(c)), the min*WFR*·Tvis value for any orientation should be between 0.30 and 0.475 for θ between 0° and 35°, respectively.

3.2. Maximum *WFR*·g-values to ensure a specific thermal comfort class

The aim of this section is to develop a solar radiation-based prediction method for maximum *WFR*·g-value (max*WFR*·g-value) depending on the AISR of the office room to fulfill different levels of thermal comfort level. We propose the metric maximum *WFR*·g-value to achieve a certain level of thermal comfort class (minimum, medium, or high) as the main design variable, since it includes room dimensions (*rw* and *rd*), window dimensions (*ww* and *wh*), and g-*value*. Thus, max*WFR*·g-value recommendation depends on *ro*, θ and the construction materials of the room.

In Fig. 10(a), the linear correlation coefficient R^2 for different AISR values, room orientation, and *SCC* values is shown. Since there is a strong correlation ($R^2 \geq 0.97$) between *SCC* and AISR for all the orientations and both construction materials, *SCC* can be predicted with linear fitting. However, a solar radiation-based prediction method considering not exceeding max*WFR*·g-value of 80, 60, 40 W/m^2 represent the simplest, most accurate, and conservative design recommendations. Once *SCC* results were obtained from annual energy simulations with IDA-ICE software, for each *WFR*·g-value the maximum *SCC* value is searched (orange circles in Fig. 10(b)). Then, we indicated with max*WFR*·*g*-value_{80}, max*WFR*·*g*-value_{60}, and max*WFR*·*g*-value_{40}, the max*WFR*·g-value, whose minimum *SCC* does not exceed 80, 60, and 40 W/m^2, respectively (Fig. 10(b)).

Once max*WFR*·g-value_{80}, max*WFR*·g-value_{60}, and max*WFR*·g-value_{40} were obtained for both construction materials, we can build rules of thumb for different room orientation and AISR (Fig. 11). According to the rules of thumb to achieve any level of thermal comfort, the

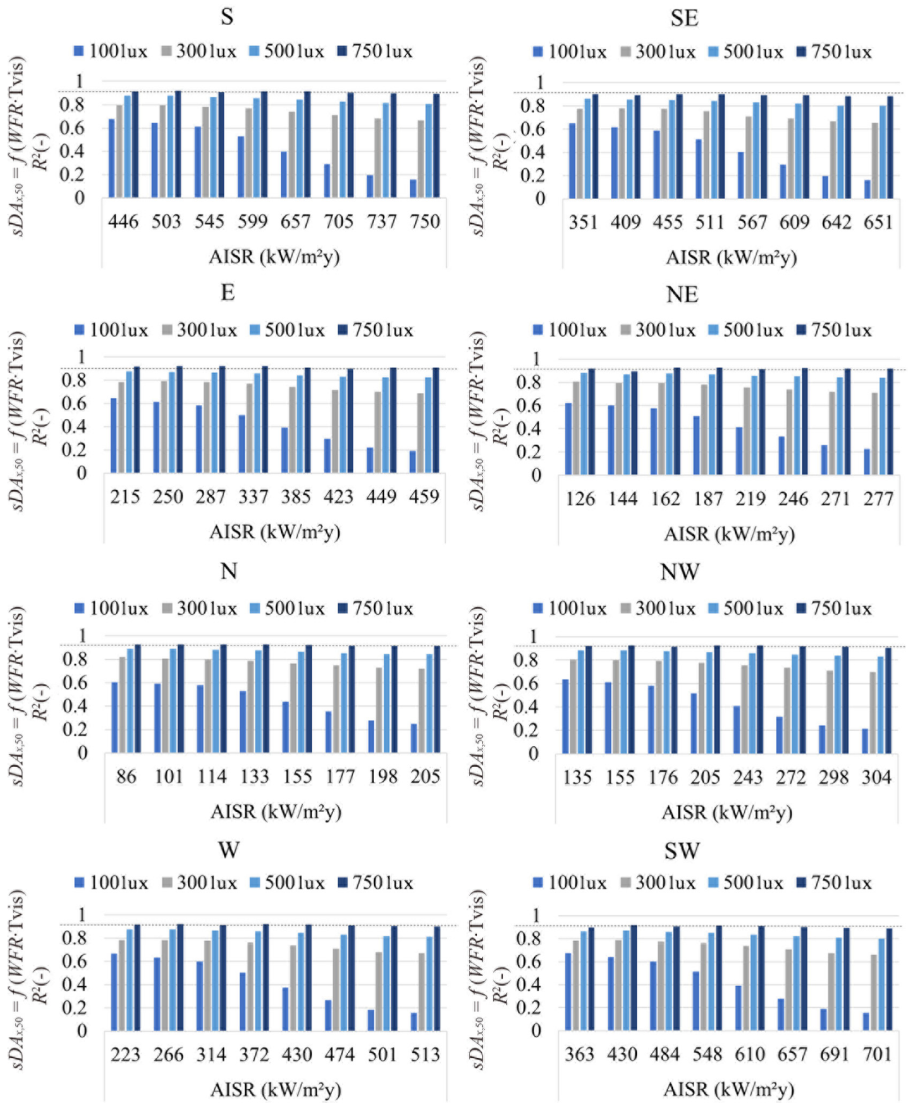

Fig. 6 Correlation coefficient R^2 between $sDA_{x,50}$ and *WFR*·Tvis for different AISR values, room orientations, and illuminance thresholds *x* (100, 300, 500, and 750 lux).

maximum recommended max*WFR*·g-value is 0.18 and it is related to north-oriented concrete-based office rooms. The most critical room orientation is S as it is related to the minimum (most restrictive) max*WFR*·g-values: 0.16, 0.12, and 0.08 to achieve a minimum, medium, and high level of thermal comfort in concrete-based office rooms.

3.3. Prediction accuracy of the solar radiation-based prediction methods

The aim of this section is to quantify the level accuracy of the solar radiation-based prediction methods to predict level of fulfillment for daylight provision and thermal comfort classes. We consider the percentage of room combinations whose level of daylight provision and thermal comfort are correctly, under (conservative prediction), and wrongly predicted. The design workflow selected was the second one, for which Tvis and g-value are input and min*WFR* and max*WFR* are calculated. We used the design workflow 2 that was implemented as open-source tool, and modified it to compare the calculated mean*WFR* from min*WFR* and max*WFR* values (average value between min*WFR and* max*WFR*), which were obtained from daylight/thermal comfort prediction methods with actual *WFR* values.

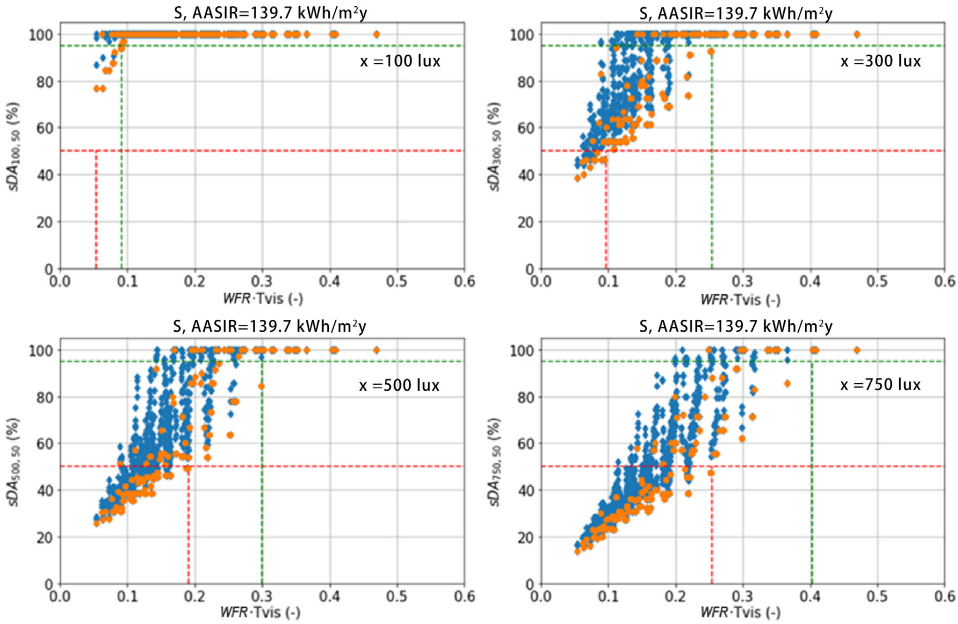

Fig. 7 Spatial Daylight Autonomy ($sDA_{x,50}$) for unobstructed ($\theta = 0^{\circ}$, accumulated AISR = 139.7 kWh/m^{2}y) south-oriented room with different *WFR*·Tvis combinations and different illuminance thresholds (x = 100, 300, 500, 750 lux).

The level of prediction accuracy for different level of thermal comfort and daylight provision is shown in Fig. 12. The maximum percentage of wrong predictions, in any case, is less than 2.5% (Concrete-based construction, high level of thermal comfort). The mean percentage of right predictions of thermal comfort classes is high; 98.7% and 98.8% for rooms with concrete-based rooms, respectively. This high accuracy is due to the high level of correlation between *SCC* and max*WFR*·g-value (Fig. 6). The existence of wrong predictions could be due to arithmetical errors when subtracting min*WFR* to max*WFR* values for each room (e.g., absolute differences of 1e-3). The mean percentage of right predictions of minimum, medium, and high level of daylight provision is 100%, 75.6%, and 88.7%, respectively. This low accuracy (for medium and high level) is due to a combination of two decisions: (1) the low level of correlation between *sDA* and min*WFR*·Tvis and (2) the conservative selection approach that we used to define the min*WFR*·Tvis for each AISR value (Fig. 9). Moreover, it was expectable to have much more number of conservative than wrong prediction (Fig. 12) specifically because the later decision to generate the rules of thumbs. This accuracy analysis tells that in order to achieve a medium or high level of daylight provision, the proposed prediction model might not be reliable enough if the designer does not accept conservative predictions.

For the prediction of daylight classes, the percentage of conservative recommendations is higher than wrong predictions: up to 23.9% versus 0.64%. Moreover, the existence of wrong predictions could be due to arithmetical residuals when subtracting min*WFR* and max*WFR* values for each room (e.g., absolute differences of 1e-3) as well as the existence of double-threshold requirements for the *sDA* metric (Table 2), whereas the *SCC* does only have one threshold per thermal class defined in Section 2.3. In summary, we can determine that solar radiation-based prediction methods could be accurate, depending on the accepted level of accuracy needed, thermal classes, and daylight classes considered. In overall, the probability to obtain a conservative prediction of the medium/high-level daylight classes of a room is 6.7% higher in absolute terms when using solar radiation-based prediction method for daylight provision. This analysis provides a sense of how well, the developed solar radiation-based prediction methods, can predict the different levels of daylight provision and thermal comfort in room combinations generated by our parametric model.

3.4. Design workflow(s) to balance thermal and visual comfort

Based on the presented solar radiation-based prediction methods for min*WFR*·Tvis and max*WFR*·g-value generated from the parametric model, we propose two main design workflows to be used by architects and designers during early design stages. The main design workflow consists of four steps (Fig. 13):

1) Building massing and external facade generation (test surfaces representing possible room's location) according to the designer's criterion that might be influenced by factors such as client's requirements, aesthetics, construction materials, solar rights of the surrounding buildings (i.e., solar envelopes (De Luca and Dogan,

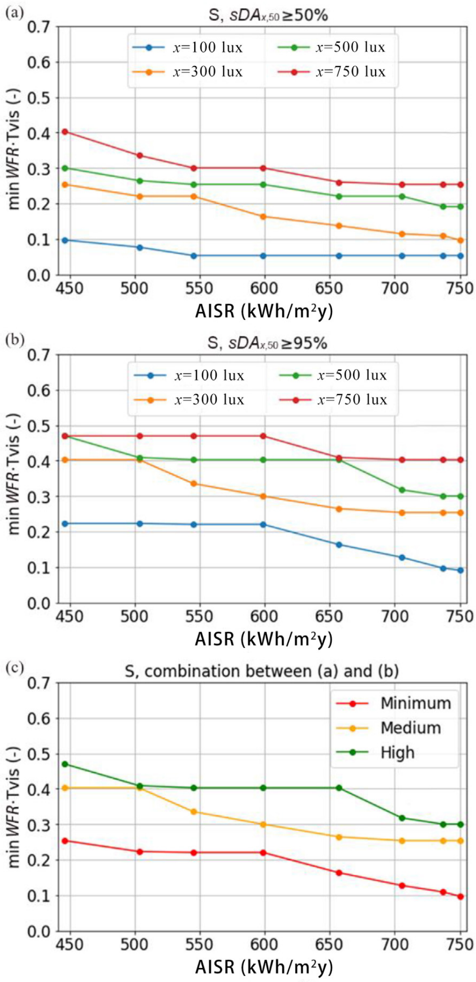

Fig. 8 Minimum recommended *WFR*·Tvis for south-oriented rooms depending on the accumulated AISR to achieve a $sDA_{x,50}$ of 50% (a), 95% (b), and different levels of recommendation of daylight provision (c) according to the method 2 (based on the *sDA*) defined by the EN 17037:2018.

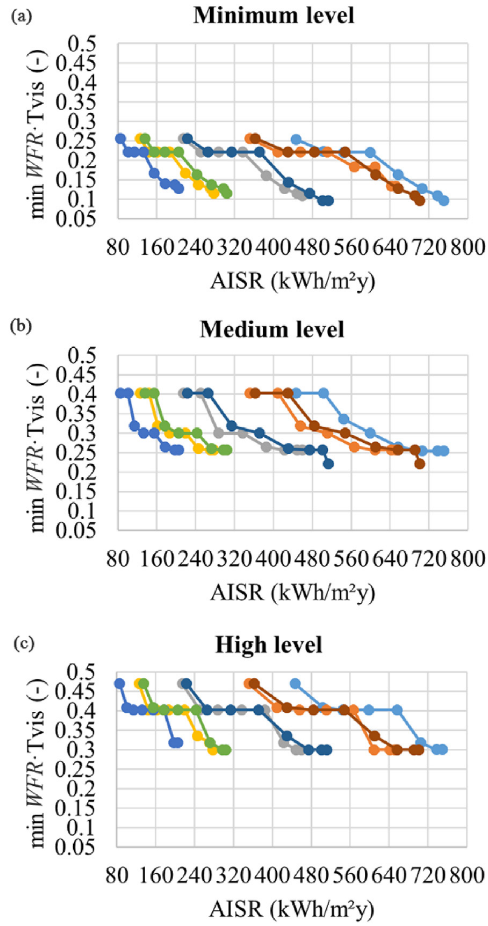

Fig. 9 Minimum recommended *WFR*·Tvis depending on the room orientation and the accumulated AISR to achieve a minimum (a), medium (b), and high (c) level of daylight provision according to the method 2 (based on the *sDA*) defined by the EN 17037:2018.

2019)), passive cooling and heating massing strategies (Sepúlveda and De Luca, 2022), accessibility, location of windows, required floor-area ratio, etc.

2) An annual solar simulation is needed to quantify the accumulated AISR for each test surface.
3) Firstly, for a desired level of recommendation for daylight provision, the selection of the min*WFR*·Tvis considering *sDA*-based criterion can be made (Fig. 9). Secondly, for a desired level of recommendation for thermal comfort, the selection of the max*WFR*·g-value (Fig. 11).
4) To use min*WFR*·Tvis and max*WFR*·g-value for each test surface as practical information for the designer.

3.5. Facade optimization case

The aim of this section is two-fold. On one side, we show how the solar radiation-based prediction methods could be applied for the facade optimization of an SE-oriented office building that will be developed in Tallinn, Estonia (design workflow 2: chosen *WFR* unknown glazing properties, Fig. 13). On the other side, detailed daylight and thermal simulations are conducted to quantify the level of reliability that the solar radiation-based prediction methods could have in existing case studies where the surrounding buildings do not represent an urban canyon. The building has a rectangular shape and an interior courtyard. The optimization problem consists of finding the properties of the glazing system (g-value and Tvis with an LSG of 2, as considered in our parametric model) and *WWR* for each of

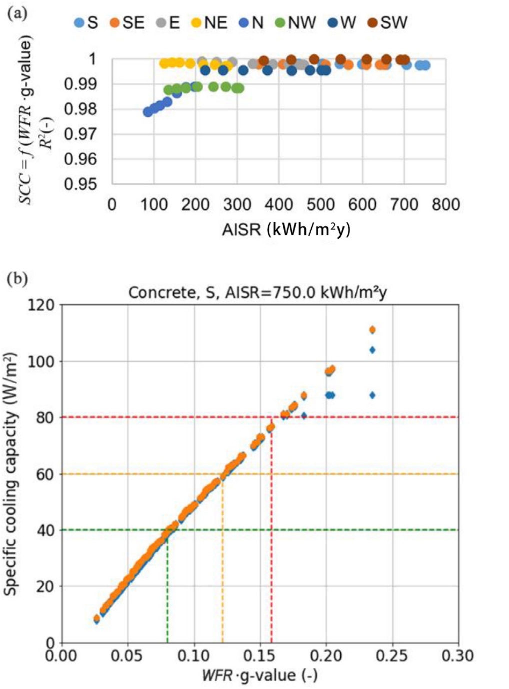

Fig. 10 Correlation coefficient R^2 between *SCC* and *WFR*·g-value for different AISR values and room orientations (a) and *SCC* for unobstructed ($\theta = 0°$, accumulated AISR = 750.0 kWh/m^{2}y) concrete (a) south-oriented room with different *WFR*·g-values combinations (b).

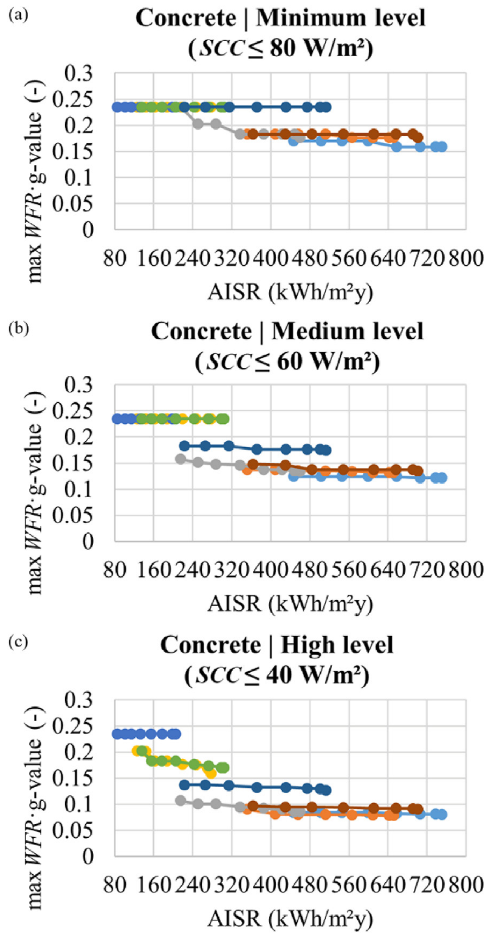

Fig. 11 Maximum recommended *WFR*·g-value depending on the room orientation and the accumulated AISR to achieve a minimum (a), medium (b), and high (c) level of thermal comfort.

the 162 test cells, which represents the potential location of medium size office rooms (5 m × 5 m).

The first step to optimize both facades is the solar radiation analysis (Fig. 14(a)). Note that there are test cells that are recognized by the workflow because the AISR (158 instead of 162) values are out of the range considered in the generated solar radiation-based prediction methods in this investigation, and therefore the validity of the recommendations whether to propose a min*WWR* or max*WWR* might be compromised. Specifically, one solar radiation analysis was conducted with LadyBug Tools to calculate AISR on each test cell, needed by solar radiation-based prediction method for daylight provision (to predict min-*WWR*·Tvis). In Fig. 14(a), the maximum AISR values are concentrated in the upper floors of the SE facade, the lowest values are related to lower floors, and the characteristic distribution is due to the skyline of the multi-tower neighboring buildings.

The optimal facade solutions to fulfill different combined requirements between thermal comfort and daylight provision were generated in less than 73,152 room combinations in 80 s (0.00109 s/room−1.1 ms/room) of computation time by using the developed open-source GH plug-in "HealthyFacadeGenerator" (Fig. 14(b−j)). The optimal facade solution for each design criteria combination has the maximum Technical Feasibility Ratio (*TFR*), which is the percentage of the room combinations whose *WWR* (calculated as the mean value between min*WWR* and max*WWR*) are between the minimum and maximum technically possible if considering the type of window dimensions of the parametric model explained in Section 2.1. The secondary criterion to select the optimal facade solution was the mean max*WWR*-min*WWR* (m*Wd*), which quantifies the selection margin the designer would have to select the *WWR* value. For instance, to achieve a minimum level of thermal comfort and a medium level of daylight provision, predicted optimal *WWR* values (with g-value = 0.29 and Tvis = 58%) are between 59% and 67% (Fig. 14 (k)), which correspond to low and high AISR values (Fig. 14 (a)).

For minimum, medium, high level of thermal comfort; *TFR* decreases with the daylight class: 100%, 100%, 52.5%; 100%, 93%, 0%; and 77.8%, 0%, 0% for a minimum, medium, and high level of daylight provision, respectively. Thus,

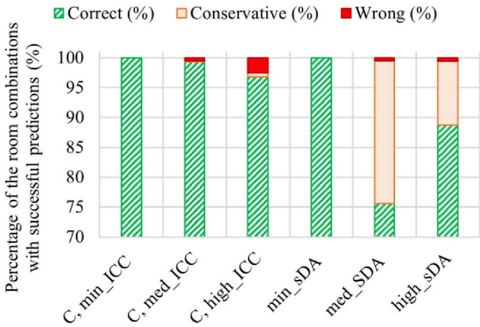

Fig. 12 Percentage room combinations (%) whose predicted thermal comfort/daylight provision levels by the solar radiation-based prediction methods for different construction types for interior walls and daylight criteria are correct, conservative, and wrong predicted. min = minimum, med = medium, *ICC* = thermal comfort class.

room facades with lower AISR become critical to fulfill medium and high level of daylight provision. Most of optimal g-values are 0.35 and the related Tvis values are 70%, meaning the achievement of certain level of daylight provision in this optimization case is more challenging than ensuring levels of thermal comfort for most of the design criteria. The higher daylight and/or thermal comfort requirements the more critical rooms located at first floors become, this is due to a combination of higher obstruction of the surrounding buildings and the south orientation of the building corner (Fig. 14 (d), (f) and (h)). In conclusion, fulfilling high-level daylight and thermal comfort simultaneously requires advanced facade solutions (i.e., dynamic shading) and/or careful cooling system design. For instance, rooms located in the bottom corner of the building could be used as rooms that do not have permanent occupancy and therefore are not critical from an indoor comfort perspective (Fig. 14 (d) and (f)). The accuracy of the method to predict the level of combined fulfillment can be seen in Fig. 15 (related to optimal cases shown in Fig. 14).

As can be seen, solar radiation-based prediction methods predicted medium-high *WWR*s, which in practice could be in conflict with energy efficiency during the cold season. Simulations of *sDA* and *SCC* were conducted for 158 rooms for each of the 9 design criteria and compared with predictions generated by the tool "HealthyFacadeGenerator":

- **In terms of daylight provision** (Fig. 15 (a) and (b)): In average, 65% of the prediction are correct (Design-*WWR*>min*WWR*). There are only wrong predictions when considering design criteria D0T2 and D1T2 with relative deviations below 22% (Fig. 14(b)). For a minimum level of thermal comfort, the agreement between predictions and actual building performance was 85.4%, 24.1%, and 22.2% for minimum, medium, and high level of daylight provision, respectively. For a medium level of thermal comfort, the agreement between predictions and actual building performance was 74.1%, 18.4%, and 100% for minimum, medium, and high level of daylight provision, respectively. For a high level of thermal comfort, the agreement between predictions and actual building performance was 69%, 90.5%, and 100% for minimum, medium, and high level of daylight provision, respectively. For design criteria different than D0T2 and D1T2, conservative predictions account up to 81.6% with a mean of 33.6%. Conservative predictions are in line with the conservative approach used to generate solar radiation-based prediction methods for daylight provision. Nevertheless, the method gives the user the best design solution (i.e., *WWR* when using design workflow 1), whose building performance is close to the combined fulfillment.
- **In terms of thermal comfort** (Fig. 15 (c) and (d)): In average, 89.7% of the prediction are correct (Design-*WWR*≤max*WWR*). Although wrong predictions are up to 67.1% (D1T0), the mean relative deviations are below 6.7% (Fig. 15 (c)) whereas the maximum relative deviation does not exceed 12.3%. As for daylight provision, the

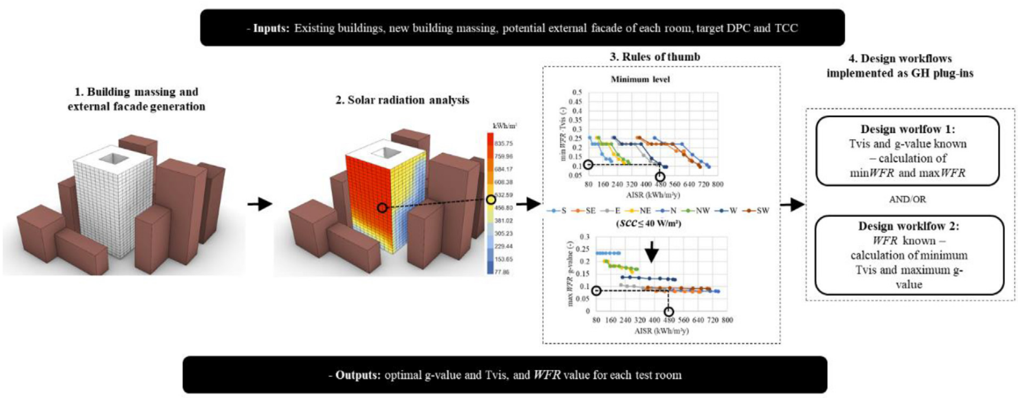

Fig. 13 Design workflows based on solar radiation-based prediction methods to achieve different level of recommendations of daylight provision (according to the EN 17037:2018) and thermal comfort.

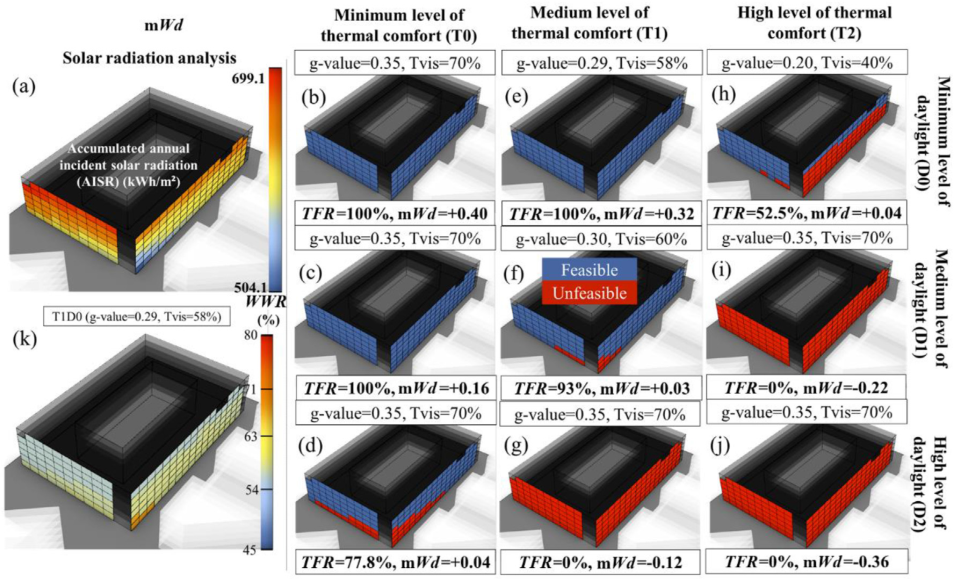

Fig. 14 Solar radiation analysis (a) required by the solar radiation-based prediction methods implemented as an open-source GH plug-in "HealthyFacadeGenerator" and optimal facade solutions to fulfill different combined requirements (b—j) between thermal comfort and daylight provision. (k) predicted optimal *WWR* values.

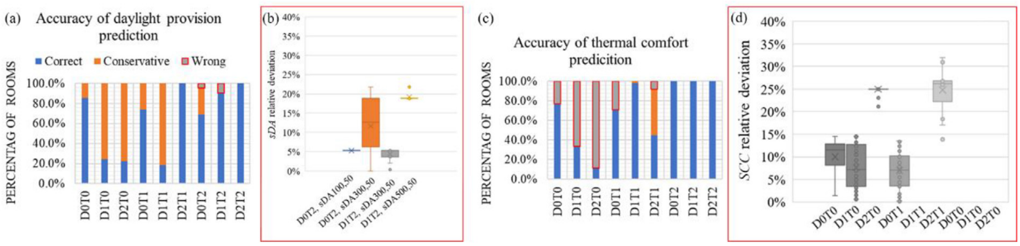

Fig. 15 Accuracy analysis of the optimization case for different design criteria: (a) daylight provision, (b) *sDA* deviations analysis, (c) thermal comfort and (d) *SCC* deviations analysis. *D* = level of daylight, *T* = level of thermal comfort, 0 = minimum, 1 = medium, 2 = high, min = minimum, and m*rd* = *sDA* mean relative deviation.

method gives the user the best design solution, whose building performance is closer to the combined fulfillment. In this case study, the prediction of the daylight provision class is less accurate and more conservative than the thermal comfort class. However, the magnitude of the relative deviations can be acceptable during the early design stages, when the number of design options is too large and the computation time is more critical than the accuracy of the performance calculations.

Regarding computation time, the use of the proposed solar radiation-based prediction methods implemented in the tool is totally justified: apart from the iterative process to select an initial design solution which could be based on experience or simulations, the time savings during early design stages for each design criterion (combination between desired daylight and thermal class) is at least 99.9982% (1.2 ms/room vs 68.35 s/room), meaning that the window sizing could be 57,000 faster than a traditional simulation based approach.

A recent study developed a machine-learning (ML) prediction model to predict daylight and thermal comfort classes in Estonian office buildings, which could optimize through a genetic algorithm (GA) glazing properties and window size per floor in a SE-oriented facade (Sepúlveda et al., 2023). The computation time required by the ML approach was more than 23 s/room, much higher than the method proposed in this research. Although the accuracy of the ML predictive method was not assessed, the possibility the *TFR* was 100% due to the floor-by-floor approach of the optimization method. In terms of purely daylight and thermal comfort classes' predictions, ML-prediction method and the proposed method based on rules of thumb could be quite similar except for medium and high daylight provision levels (Fig. 12). Finally, the available tools and required software could make the use of these methods more or less attractive for designers, on one hand; the ML-GA method requires the use of python and grasshopper independently. On the other hand, the design workflows proposed were implemented as compact Grasshopper components for Rhinoceros, that might be easier to use by designers in practice.

4. Conclusions

There is a need to understand correlation between obstruction angle and incident solar radiation/daylight provision/cooling capacity for different facade orientations to balance daylight and thermal comfort in office buildings, especially in cold climates where there is a poor daylight availability during the cold season and high thermal mass constructions. In order to fill this research gap, the main aim of this investigation is to develop easy-to use solar radiation-based prediction methods for the design of office buildings facades (i.e., decisions: room size, *WFR*, Tvis, g-value) located in urban canyons to balance daylight provision according to the EN 17037:2018 and thermal comfort. Firstly, the scientific novelty of this investigation lays on the correlation study between the mentioned design variables and building performances (*sDA* and *SCC*). Secondly, the development of solar radiation-based prediction methods can help architects and designers to work more efficiently during early design stages and to obtain more performative solutions in much shorter time. The findings of this investigation are as follows:

- The proposal of easy-to-use solar radiation-based prediction methods to be used by architects and practitioners to balance thermal comfort (through *SCC*) and daylight provision (through *sDA*) during early design stages is possible. Thus, the solar radiation-based prediction methods are combined in two proposed design workflows not based on detailed daylight or thermal simulation, whose input is solar analyses from the building massing stage. The output of these workflows can be whether an optimal *WWR* or g-value/Tvis for each test room.
- The prediction accuracy of the solar radiation-based prediction methods depends on the desired daylight and thermal comfort classes. Considering a parametric model, which contains 61,440 rooms, the percentage of correct/conservative prediction are higher than 97.6%.
- By using the first design workflow, the facade optimization of 73,152 office rooms considering 9 different combinations of daylight and thermal comfort requirements was conducted. The building performance of an average of 77.4% rooms were correctly predicted. Apart from the time savings related to the iterative process to select an initial design solution which could be based on experience or simulations, the proposed design method is 57,000 times faster (1.1 ms/room) than a traditional approach based on daylight and energy simulations. Furthermore, the design method based on solar radiation-based prediction methods proposed in this investigation could suppose a game changer for architects and designers during early design stages within the Estonian context.

The proposed solar radiation-based prediction methods were developed considering concrete-based side-lit office rooms in the climatic context of Tallinn, Estonia. In addition, the conservative approach of selecting the most critical building performance values for each design variable could be further investigated. Despite the computation time efficiency, the level of prediction accuracy could vary depending on the case study. Solar radiation-based prediction methods could be improved by adding the energy efficiency during the cold season as a design criterion since it would limit the maximum *WFR* of the room study. There were only considered eight main room orientations, meaning that the accuracy of the design method for other orientations are unknown and might be explored in future research. The solar radiation-based prediction methods cannot give recommendations when the external facade of the room has an ASIR value out of a range that depends on the room orientation. The exclusive consideration of the direct and diffuse component but not the reflected solar radiation might make design recommendations from solar radiation-based prediction methods to overestimate thermal comfort levels. Thus, future research could be: to study the viability of the generation of the developed solar radiation-based prediction methods in other climatic context and type of buildings; the comparison of the proposed design workflows with other existing facade design methods in terms of accuracy and computation time; and qualitative evaluation of the proposed method by architects and designers to improve it.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 4

IV

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Comparative study of using periodic daily and long-term weather data for cooling system sizing and impact of thermal mass

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Abstract

The energy efficiency of buildings is increasing due to energy performance requirements, and the basis for reaching high energy performance is a well-designed and insulated building envelope. Therefore, office buildings' cooling needs depend primarily on solar and internal heat gains, whereas outdoor temperature has a significantly smaller effect. Furthermore, the highest cooling capacities may occur in spring or autumn when the solar angles are smaller. For that reason, the cooling systems of office buildings are required to be sized based on dynamic building performance simulations. Most of such designs in Northern Europe are performed using IDA ICE simulation software, which uses the ASHRAE Fundamentals heat balance method by default. The design calculations are carried out using a periodic steady-state method which consists of repetitive simulations of selected hot days until the building is not heated up from day to day using the final designed cooling capacity. The process of heating the space by thermal loads in buildings with high thermal mass and well-controlled solar heat gains takes a longer time than in traditional buildings. Thus, the effect of building thermal mass on reducing the design cooling loads might be underestimated.

In this paper, we analyze to what extent the ASHRAE Fundamentals method underestimates the effect of the building thermal mass. For this purpose, the cooling system sizing with a focus on a zonal level according to the ASHRAE handbook is compared to the system sizing results of a 30-year simulation using IDA ICE simulation software. A hypothetical office building with four offices toward North, West, South, and East is developed and used for the simulations. The building body comprises four alternatives A to D, which can also be called: very light, light, heavy, and very heavy. The study showed that the current method of cooling design did not significantly underestimate the thermal mass effect in buildings with heavy construction. The thermal mass impact was at its maximum in the southern office, resulting in 5 W/m2 or approximately 20% difference between structures A and D's cooling capacities using both simulation methods. The difference between results from simulation methods is negligible. However, the simulations for more accurate cooling system sizing with criteria related to the operative temperature need to be done using specific weather files developed for simulations in longer periods.

Introduction

Recent years have seen increased interest in buildings with net-zero or near-zero energy usage. The energy performance requirements are in place to help cut down the amount of energy used in buildings (Eleonora, Frey, & Rizzi, 2013). A well-insulated and well-designed building envelope is the foundation for high energy efficiency in buildings. Passive solutions for decreasing cooling and heating demand, implementing renewable energy systems, and using more efficient HVAC (active) systems are the primary design considerations for such structures. Some passive solutions, including shadings, natural ventilation, passive façade design, high thermal mass, etc., can be utilized to remove or decrease some of the heat gains for effective cooling design (Oh, et al., 2017).

In highly insulated buildings, the thermal load from higher outdoor temperatures is reduced, and the share of contribution by internal heat gains and solar gains to the thermal loads and cooling system sizing is increased. Therefore, in the countries with higher latitude, specifically colder climates in Europe, the highest cooling capacities may occur in spring or autumn when the solar angles are smaller. This is, however, limited to the north-faced and south-faced offices. (Thalfeldt & Kurnitski, 2014) As a result, office building cooling systems must be sized using dynamic building performance simulations. Most of these simulations in northern Europe are conducted using IDA ICE simulation software, which uses the ASHRAE Fundamentals heat balance approach (American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2017) by default. (EQUA, 2013) The approach uses a periodic steady-state method that consists of repetitive simulations of selected hot days until the building does not become overheated from day to day when the final designed cooling capacity is used, at which point the design calculations are completed. Structures with high thermal mass and well-controlled solar heat gains take longer to heat than buildings with low thermal mass and lower solar heat gains. As a result, it is possible that the impact of building thermal mass on reducing the design cooling loads has been underestimated.

This research focuses mainly on identifying and possibly quantifying how much the steady-state method for cooling sizing underestimates the impact of thermal mass. Regardless of how much building materials can contribute to cooling, they may store heat and release it when the temperature difference is large enough. (Sarbu & Sebarchievici, 2018) The key influence of thermal mass is the so-called "peak shifting," which implies that at the peak periods of cooling demand, storage can supply some of the demand to minimize strain on active cooling systems that may lead to smaller HVAC systems. (He, 2004)

This article aims to determine the extent to which the ASHRAE Fundamentals method underestimates the influence of building thermal mass. To do this, the cooling system sizing results from a 30-year simulation using IDA ICE simulation software (EQUA, 2013) are compared to the cooling system sizing results from a zonal level based on the ASHRAE handbook. The simulations are conducted using a generic office building with four offices facing North, West, South, and East. The structure's body is composed of four distinct components, referred to in this study as very light, light, heavy, and very heavy.

Methods

In this paper, two types of simulation methods are called long-term simulation (30 years simulation) and steady-state method (ASHRAE method).

The main steps for this study are summarized below.

1- A generic office building model is developed with four offices. Each office has its windows in one direction, South, East, West, and North
2- The variables of this study are building body and window sizes/glazing. The building body types are four alternatives, A, B, C, and D. The Windows types are also four alternatives, small and Big windows, with and without shadings.
3- For each variation, a specific model is generated and then simulated using long-term (30 years) Simulation and ASHRAE steady-state method.
4- The cooling system capacities were then compared to reflect the amount of cooling sizing underestimation by the steady-state method.
5- Latterly, the operative temperature of two selected cases is analyzed to check if they satisfy EN 16798 standard. The criterion is to have a lower operative temperature than 26°C in 97% of the occupied hours during cooling seasons. (EN 16798-2, 2019)

Figure 1 depicts different alternatives for building bodies with the same architectural layout, and Table 1 shows the two alternatives' windows specifications used in the simulations. The general plan view of the offices is shown in Figure 3, and the three-dimensional view of different windows and shading alternatives is shown in Figure 4.

Four types of structural profiles comprised of walls, floors, and ceilings have a thermal mass difference, which is indicated in Figure 1. Thus, we produced 16 different case studies using a combination of two window sizes, two shading strategies, and four structural profiles for each. The simulation results from the ASHRAE method and long-term simulation using a 30-year climate file are compared.

Several parameters were determined based on EN 16798-1 (European Standard, 2019) or assumptions to facilitate the study. These parameters were as follows:

- The number of occupants in each office was 10, and the installed power of equipment and lighting was 12 W/m^2 and 6 W/m^2, respectively,
- The supply air temperature was 18 °C,
- The offices and the staircase had a Constant Air Volume flow of 1.4 l/(m^2·s) during working hours with one hour margin. The flow outside of the working hours is the minimum amount (0.21 l/(m^2·s)) to take into account the ventilation of toilets, cleaning equipment room, etc. ventilation working on part load.
- The windows had internal blinds drawn when the incident solar radiation on the outside of the glazing exceeded 100 W/m^2. The specifications are mentioned in Table 1,
- The room temperature setpoint was 25°C,
- Internal walls were the same in Three types of structures, A, B, and C. The layers were: 30mm of light insulation and 52mm of gypsum. The internal wall for the D type is just a layer of concrete of 300mm in width.
- The office is located in Tartu, Estonia.

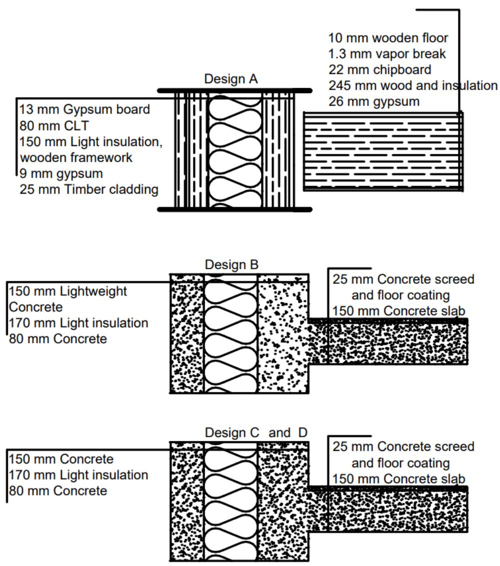

Figure 1: Structural design types of the case studies.

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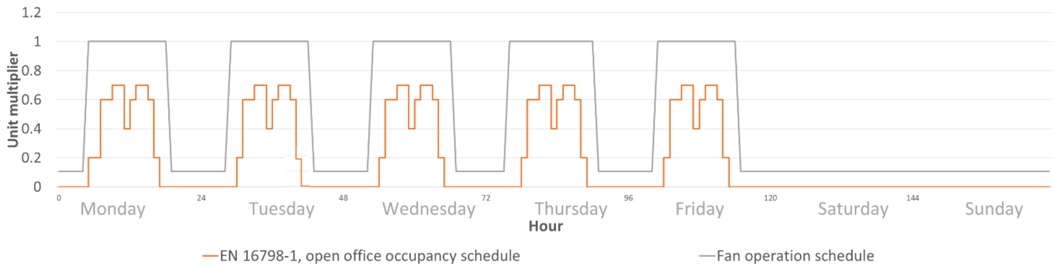

Figure 2: The occupancy and fan operating schedules used in this study.

Table 1: Windows and internal blinds specifications.

Windows group	1 (small)	2 (big)
Width m	1.8	2.1
height m	1	1.9
Area	1.8	3.99
WWR	0.25	0.58
Total windows per office	7	7
Number of layers	3-pane	4-pane
Solar heat gain coef. (SHGC)	0.49	0.32
T. Solar transmittance	0.41	0.28
Visible transmittance	0.71	0.59
Glazing U-value	0.6	0.6
Internal emissivity	0.837	0.837
External emissivity	0.837	0.837
Internal blind solar gain factor	0.65	0.65
Internal blind short-wave shading coefficient	0.16	0.16
Internal blind U-value multiplier	1	1

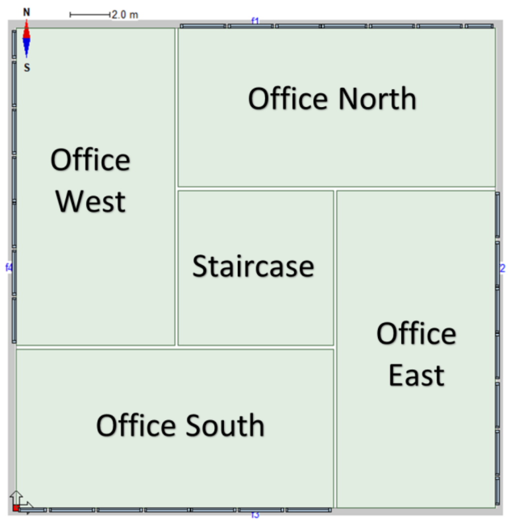

Figure 3: General office plan, 24.5m x 24.5m.

The layout includes four offices with dimensions of 16m x 8m and a total space of 128 m^2. The offices were 3m high. The office used in this simulation is neither on the ground floor nor under the roof. It is a floor in the middle of an office building. This means the model does not have a roof connecting to the ambient air and a floor slab connecting to the earth.

The Simulation process for comparing the results using the periodic steady-state method and long-term simulations can be listed below:

1. A 30 years climate file from 1990 to 2020 is created for the simulations based on historical weather data from the weather station in Tartu, Estonia.
2. Multiple simulation models were created based on building bodies, windows, and shadings variations.
3. The design cooling capacities for each zone were calculated using the steady-state method and long-term simulations using the climate file for each building model.

The simulation, according to the ASHRAE method, needs the identification of design day parameters. By default, the design day parameters can be found for a year, and one set of parameters is used together with the hottest month to size the cooling systems. In this study, we generated the strictest minimum and maximum temperatures for each month according to the ASHRAE handbook and simulated all cases for every month. The minimum and maximum temperatures for the 30-year period according to ASHRAE are listed in Table 2. The maximums are 0.4 percentile of the maximum temperature data points for each month in 30 years.

Table 2: Temperatures for periodic method design days.

Month	Minimum °C	Maximum °C
Mar	13.4	16.8
Apr	20.1	24.9
May	19.5	27.7
Jun	19.7	28
Jul	20.5	28.5
Aug	19.6	28.3
Sep	19.2	27.6
Oct	16.8	18.8

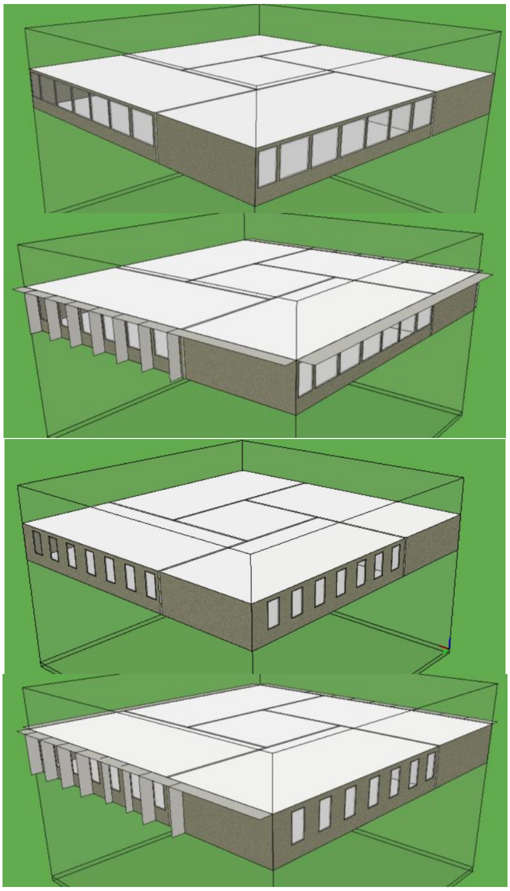

Figure 4: 3d view of the models with two different Window to Wall Ratio (WWR) and shading.

Results

The results are summarized in Figure 5. The largest design cooling capacities occurred in Southern and Eastern offices, proving the importance of solar radiation in efficiently built office buildings. The results from the periodic steady-state method by ASHRAE had the same pattern as long-term simulations. The steady-state method estimated a lower or higher value than the long-term simulation depending on the case study variables. This difference ranges between 1 – 4 W/m^2 for all designed cooling capacities, while it can also be seen that thermal mass does not have a significant impact, as the design cooling capacity difference between structures A (the lightest) and D (the heaviest) levels ranged between 1 – 5 W/m^2 for all cases. The thermal mass impact is at its maximum in the southern office, resulting in 5 W/m^2 or approximately a 20% difference between structure A's and structure D's cooling capacities using both simulation methods. Moreover, the duration curves visible in Figure 8 reflects that the higher the thermal mass, the lower the average operative temperature during cooling periods. The number of hours with an operative temperature higher than 26°C was also higher in buildings with lower thermal mass. Therefore, the overall thermal comfort was better in case studies with higher thermal mass.

The general trend of the results shows that occasionally the long-term simulations resulted in higher cooling capacities. This trend is at the highest for offices with bigger windows without external shadings. This was due to the fact that solar irradiance had much more effect on the sizing of the cooling system using the periodic steady-state method by ASHRAE, which assumes a clear sky for the sizing process. In contrast, in long-term simulation, the sky can be cloudy.

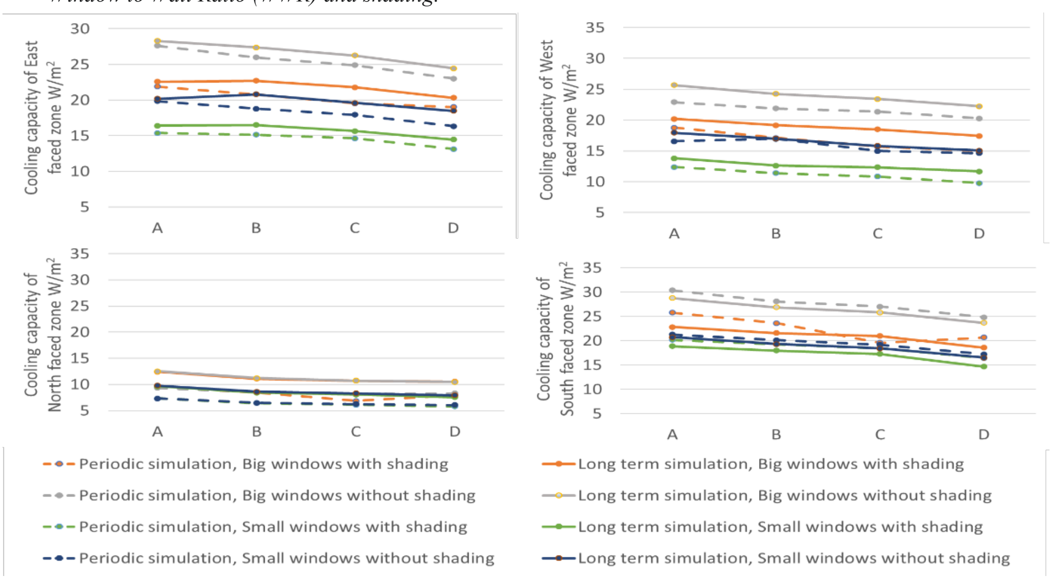

Figure 5: the cooling design capacities for different building bodies, window sizes, and shadings.

The window sizes do not affect the cooling capacities for north faced office, indicating the lower impact of solar irradiance in that office. The critical months for determining the cooling system capacity with the steady-state method were in June, July, and August for North, East, and West offices, while for the Southern office, September was the critical month. This is due to the solar radiation effect in such efficiently built offices. Solar radiation has a lower angle during September compared to the summer months; therefore, solar loads were higher in autumn in the office toward the south. To analyze the results in detail, two selected cases are compared. The Big window, no shading settings, and the east and south offices are chosen to have the maximum effect of the sun in the detailed analysis. For structure, a heavier structure body (type D) is selected to include the minor thermal mass effect in the analysis as well. In long-term simulations with actual weather data, the day that the cooling system size peak occurred for office east was the 6th of July 2009, and the date for the Southern office was the 9th of September 2019. The radiation and temperatures of the specific days are presented alongside periodic synthetic climate parameters in Figure 6 and Figure 7.

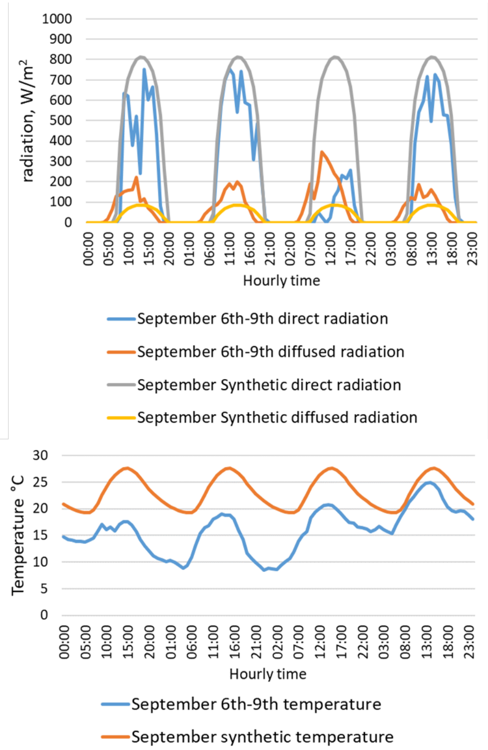

Figure 6: Comparative climate parameters curves for Simulation results in September for both long-term (6th to 9th of September 2019) and periodic (Synthetic climate) simulations

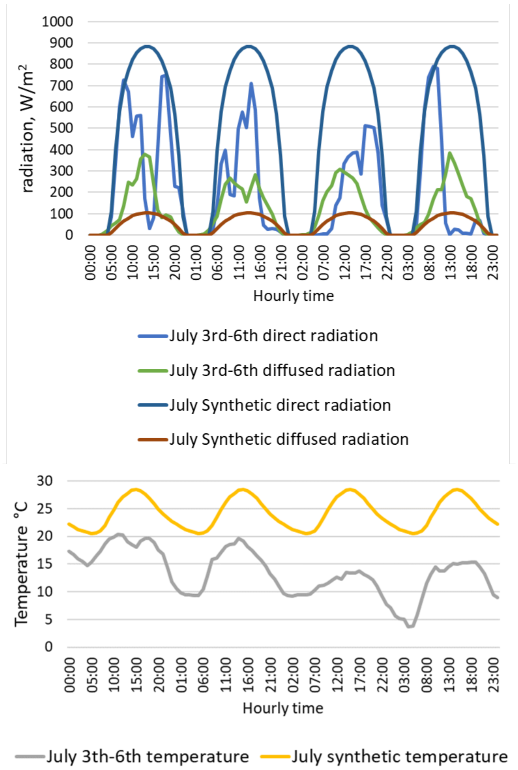

Figure 7: Comparative climate parameters curves for Simulation results in July for both long-term (3rd to 6th of July 2009) and periodic (Synthetic Climate) simulations.

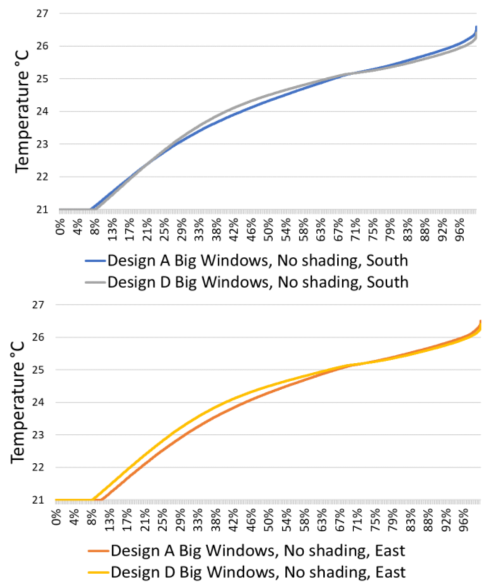

Figure 8: Duration curve for operative temperature in selected cases and offices, temperatures higher than 21 °C are presented only for difference magnification.

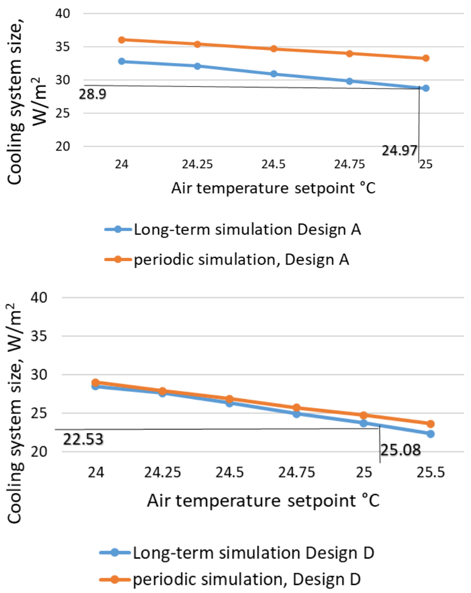

Figure 9: Cooling capacities for different air temperature setpoints for selected cases, A and D for the southern office without shading.

The adjusted setpoints for two selected cases, design A and design D for office south, are 24.97 °C and 25.08 °C, respectively. This means that to compare the two cases considering the operative temperature criterion from EN 15798-1, design A and design D should be simulated with an air temperature setpoint of 24.97 °C and 25.08 °C, respectively. The results are shown in Figure 9. The differences are small, but the difference for designed cooling system size is more in long-term simulations after adjusting the set point. It means that the importance of thermal mass can be more than what is assumed in ASHRAE periodic design method.

Discussion

The long-term simulations resulted in smaller system sizes for offices in the south and bigger capacity for offices in other directions compared to the periodic steady-state method. For calculating the design day, the strictest category, 0.4 percentile of the descending temperature data points, is used as maximum temperature. This can be further studied to what extent the cooling system sizes and thermal comfort is impacted if other percentiles are used for cooling sizing. Additionally, conducting 30-year simulations is not feasible in practice, and further work is needed to determine the weather conditions for dimensioning the room cooling units.

By looking at the results, sizing using air temperature setpoint _the common practice_ without consideration of operative temperature becomes controversial since, according to EN 16798-1:2019 (European Standard, 2019), the number of occupied hours with an operative temperature higher than 26°C should be limited to less than 3% of the total occupied hours during the cooling period. In the future, simulations can be done using adjusted air temperature setpoints to satisfy the operative temperature requirement by the standard to have a more objective comparison of the system sizes.

Moreover, the study can be done with varying building types, orientations, and ventilation strategies (e.g., night cooling) to determine if the underestimation/overestimation happens in all other cases. The geometry difference studies can start with an office layout of 8 offices, 4 in one direction and 4 in a mixed direction on the edge of the layout.

Conclusion

This article aimed to determine the extent to which the ASHRAE Fundamentals technique underestimates the influence of building thermal mass. To do this, the cooling system sizing results from a 30-year simulation using IDA ICE simulation software is compared to the cooling system sizing results from a zonal level based on the ASHRAE handbook. The simulations are conducted using a hypothetical office building with four offices facing north, west, south, and east. The structure's body is composed of four distinct components, referred to in this study as very light, light, heavy, and very heavy. The study found that the current cooling design approach does not significantly underestimate the influence of thermal mass. The thermal mass impact was at its maximum in the southern office, resulting in 5 W/m² or around 20% difference between structures A and D's cooling capacities using both simulation methods, and the difference between results from simulation methods is negligible. However, simulations for more precise cooling system size considering operative temperature requirements should be conducted using weather files built for long-term simulations.

Acknowledgement

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Appendix 5

V

Seyed Salehi, S. S., Ferrantelli, A., Aljas, H. K., Kurnitski, J., and Thalfeldt, M. (2021). Impact of internal heat gain profiles on the design cooling capacity of landscaped offices. *E3S Web of Conferences*, 246, 07003. https://doi.org/10.1051/e3sconf/202124607003

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Impact of internal heat gain profiles on the design cooling capacity of landscaped offices

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Abstract. Using passive methods in façade design for controlling heating and cooling needs is an important prerequisite for constructing cost-effective nearly zero-energy buildings. Optimal control of solar heat gains reduces the cooling demand and the size of the active cooling systems. However, applying such methods increases the impact of internal heat gains on the heat balance of the buildings, and accordingly also the dimensions of cooling systems. Therefore, a good model of internal heat gains is needed for a reliable and optimal sizing of the cooling sources. This paper aims to bring understanding to developing internal heat gains models for sizing the cooling systems. For this purpose, several weekly internal heat gain profiles were selected from a large set of tenant-based electricity use measured in 4 office buildings in Tallinn. The selection was based on maximum daily or weekly peak loads of an office space per floor area. The selected profiles and the schedule of EN 16798-1 were used to dimension ideal coolers in the zones of a generic floor model with landscaped offices developed in IDA-ICE 4.8. The model had variable window sizes and thermal mass of the building materials. Finally, the internal heat gains models resulting in the largest cooling capacity were identified. We found that utilizing thermal mass can reduce the cooling system size by up to 7% on average and the models with big windows and light structure need the largest cooling systems. The cooling loads obtained with the profile of EN 16798-1 did not significantly differ from the average of other profiles' results. This paper focused mainly on the zonal dimensioning of cooling systems, therefore a more in-depth analysis of the different occupancy patterns as well as developing models for dimensioning the cooling system at the building level, is needed.

1 Introduction

Nearly zero or net-zero energy buildings are increasingly getting attention in recent years. Many countries have already provided regulations while working on road maps to reduce energy usage in the building sector [1]. The major efforts for designing such buildings are passive strategies for reducing cooling and heating demand, implementing systems for utilizing renewable energy sources and using more efficient HVAC (active) systems. In order to reduce heat gains for efficient cooling design, some passive solutions can be used, e.g. controlling heat gain from the sun using shadings, applying natural ventilation, passive façade design, etc [2]. Implementing such methods will reduce the total cooling demand of the building while it increases the impact of internal heat gains on cooling system size [3]. The internal heat gains in total cooling load are important in cold climates but not always in warm climates. In a warm climate for an old building without external wall insulations, Coşkun et al. in [4] indicate a share of internal heat gains in total cooling load as low as around 1%, while the share of electricity use for equipment usage can be up to 60% of the total electricity use [4]. However, by reducing the internal heat gains from lighting (using efficient LED lights), equipment and small power consumers, majorly laptops and monitors in office buildings, a 60% reduction in cooling loads can be achieved in certain building systems [3].

There is a long list of influential decisions during the design phase that can affect cooling loads specifically from the passive design perspective. Among them, the parameters related to the windows and the thermal mass of the building parts are focused on in this paper. The optimal window to wall ratio (WWR) has been suggested to be between 0.30 and 0.45 for all sorts of climates and building orientations [5] while considering just extreme cold climates, it is suggested to be around 0.37 or 0.6 depending on the orientation and glazing type [6]. Shadings are also important, Thalfeldt et. al. in [7] indicated that external shadings are effective to reduce cooling size demand up to 70% while suggesting a specific complex control method to achieve this. The materials that are used to construct a building can store heat and release that heat when there is a temperature difference, no matter if the designers have calculated them or not. Sarbu et al. in [8] listed selected solid-liquid materials for sensible heat storage. The most common materials are Water, Wood, Concrete, Cast

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iron, Sand, different types of Brick and Rock. On the other hand, there are Phase Change Materials (PCM) that are being used due to latent heat storage potential without temperature change, however, they are not related to this article. In a summary graph, Sarbu et al. [8] indicated selected materials for energy storage purpose that gives the reader an overall understanding. The maximum energy storage capacity of a 10-mm-thick building part operating between 18 and 26 °C for 24 h is 18 Wh/m^2 for wood while numbers for Concrete and Iron are 48 Wh/m^2 and 79 Wh/m^2 respectively. The energy storage capacity of the building components/materials can reduce the total energy required for heating and cooling, but another important impact is the so-called "peak shifting" which means that during the cooling load peak periods, the storage can meet a part of the cooling demand to reduce pressure on the active cooling system, which may lead to smaller HVAC system [9].

The procedure of estimating and calculating cooling loads in a zone must contain conductive, convective and radiative heat balance for each surface and a general convective heat balance for the zone. The main calculation method for this procedure is Heat Balance (HB) method. This method solves the problem directly through an iterative procedure in which most often a computer must be involved. However, while ASHRAE suggests Heat Balance as the most accurate method, there are several other methods for cooling load calculation described in the handbook. The Radiant Time Series (RTS) method is a simplified method based on the Heat Balance method. The benefits of the RTS method are not to be iterative and quantifies the contribution of each construction part to the total load which helps practitioners with judgements over different construction parts and zones. Nevertheless, ASHRAE mentions that the RTS method can be used for peak load design and should not be used for annual energy simulations due to its limiting assumptions. Some other methods are also accepted by ASHRAE to be used such as transfer function method (TFM), cooling load temperature difference/ cooling load factor (CLTD/CLF) method, total equivalent temperature difference/time averaging (TETDA/TA) method, but since RTS can be effectively replaced with all other methods, they are rarely used. [10]

The impact of occupants' behavior on energy consumption and HVAC design in the buildings gained attention in the late 1950's with a focus on window openings and ventilation systems. This attention turned to occupants' behavior relation with energy consumption in the 80's. A very informative chronological review of major methods for occupants' behavior modeling is done by Tam et. al. [11]. Zhao defined occupants as "active" and "passive" in the studied zone and used data mining (nominal Classification method) to classify individual behavior and label them [12]. Richardson et. al. in [13] employed the two-state nonhomogeneous Markov Chain Monte Carlo (MCMC) technique to identify active and inactive users and predict the timing of the occupants' activities. Mahdavi et. al. in [14] suggested simplified and stochastic models for predicting the annual plug loads, Stochastic-Weibull distribution is used in the study and it concluded that the stochastic model performed better in predicting plug loads peak and distribution. There are several recent studies in which deep learning and machine learning techniques are employed to facilitate a better prediction, Wang Zhe et. al. in [15] and Wang Ran et. al. in [16] both used such techniques for occupancy predictions. In a wider review, Ferrantelli et. al. gathered major methods used for such modeling techniques and selected several methods in [17] that are suitable to be used in Building Performance Simulation (BPS) software; a combination of least squares regression and correlations was chosen as the best model for predicting the annual electricity use of tenants.

The increasing uncertainties in the HVAC design process will lead to excessive oversizing of the systems. A report shows that 40% of all rooftop systems are 25% oversized in California in 2000 based on peak day load design method which means that the units are radically oversized for the much of the warm season [18].

The purpose of this study is to increase the understanding of the cooling demand *at the zone level* (i.e. not focused on the building as a whole), by considering occupancy, window size, single / open plan office and the existence of construction parts with different thermal masses which can affect the cooling system sizing. Here the different internal heat gains models will be evaluated in order to find the best model for a reliable and optimal zonal cooling system sizing. To achieve this goal, several weekly internal heat gain profiles were selected from a large set of tenant-based electricity use measured in 4 office buildings in Tallinn. The selection was based on maximum daily or weekly peak loads of an office space per floor area. The suggested occupancy schedule by EN 16798-1, alongside the selected profiles, will be used to dimension ideal coolers in the zones of a generic floor model of a landscape office plan and variable window sizes and thermal masses of the building parts. To be able to use the suggested model in practice, the internal heat gains models resulting in the largest cooling capacity were identified.

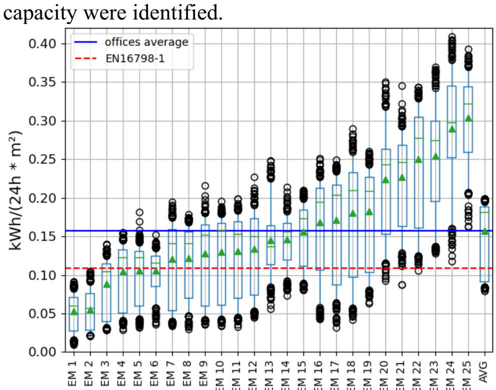

Figure 1 The distributions of data points in kWh/(24h·m²) of each measuring point in the studied building. Each EM represents a set of measured data recorded by a sensor in the numbered zone [19].

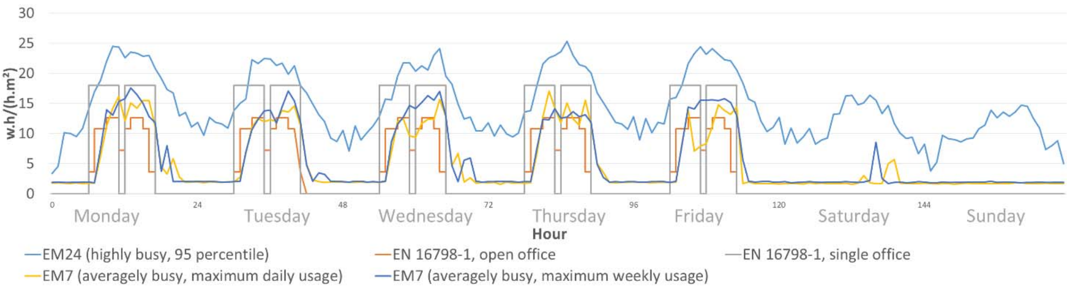

Figure 2 The weekly profiles selected for the analysis.

2 Methods

The experimental data used in this study were aggregated from four office buildings located in Tallinn, Estonia, from early 2017 to March 2020 (which coincided with the beginning of the COVID19 pandemic) [19]. Every building was divided into zones and electricity consumption was metered separately per each floor. Three-phase electricity meters per measurement point stored data from each building, for a period ranging between 11 and 27 months; the time resolution was one hour for two buildings and daily (24h) values for the other two. The data showed a prominent effect of the COVID19-induced lockdown after March [19].

A robust pre-processing provided data that were free from frequent stuck readings and abnormally high peaks, which were dealt with by a specific algorithm we developed to remove outliers while still keeping most of the information associated with the general trend. **Figure 1** is indicating the data gathered from an office building that will be studied. The boxplot whiskers are drawn on the 5th and 95th percentile, triangles are the means, the blue line is the average energy consumption (plug loads and lighting) of the building and the dashed red line is representing the EN 16798-1 values [20].

As the input data of this study, we selected two measurement points in one building considering the reference daily cumulative consumption of 0.1089 kWh/(24h·m²) that is used in EN 16798-1 [20] for modeling the energy consumption (plug loads and lights) of the office buildings. The point EM7 recorded on average 0.12, which is close to the Standard values, while EM24 displayed on average 0.28, a substantially higher value. The raw data pertained to the period from March to September (included), when the heat gains are most problematic; from the data, a week profile with the highest cumulative daily energy usage and one with the highest cumulative weekly energy usage were selected from EM7. A weekly profile with the highest cumulative energy usage was then picked from the EM24 data to represent the crowded offices. 5 weekly profiles were selected for this study, two from EN 16798-1 and three from the studied building, as can be seen in **Figure 2**.

For the analysis, we have used IDA ICE 4.8 software which uses Heat Balance as the standard method for cooling design. The study is at the individual zone level, not aimed at calculating the total cooling demand. Therefore, an ideal cooler was placed in each zone to demonstrate how much heat must be removed from it.

$$oc_t = \left(\frac{pl_t}{pl_s} - \frac{1.2 * pl_{min}}{pl_s}\right) * \left(\frac{1}{\frac{pl_{max}}{pl_s} - \frac{1.2 * pl_{min}}{pl_s}}\right) \quad (1)$$

The data-selected profiles were modeled as schedules for the equipment (plug loads) and lighting. The schedules for occupants were calculated based on these profiles by normalizing the values according to Formula (1), in which oc_t ϵ[0,1] is the occupants' presence, pl_t is the plug loads at a certain hour, pl_s is the equipment and lighting consumption according to EN 16798-1 [20], pl_{max} and pl_{min} are the maximum and minimum consumptions recorded in the weekly profile.

The structural profiles of the same architectural plan are described in detail in the charts below. Since the purpose of the study is to compare different occupancy models and increase the understanding of cooling sizing, various profiles were selected to have low and high window-to-wall ratios and low and high thermal masses. Windows glazing is 3-pane glazing for small windows and 4-pane glazing for big windows. The window sizes are listed in **Table 1**, the detailed parameters in **Table 2**. There are two types of structural profiles of the wall, floor and ceilings with a high thermal mass difference. Design A in **Figure 1** has a high thermal mass in the zones by having exposed concrete, while Design B has a low thermal mass. We thus created 4 different case studies from the combination of 2 window sizes and 2 structural profiles, where hourly design profile, weekly design profile and monthly design profile were assessed. Since we targeted to analyse the impact of thermal mass and the differences between the profiles in a longer period than a design day, we edited the climate file to mimic the warmest possible climate in the simulation period. The cloudiness was 0% on all days, the data of the warmest day of each month (e.g. 15th of June) including temperature, wind speed and radiation were copied for the whole month (e.g. June). The data for the climate file is provided in **Table 3**.

Table 1. Windows sizes in the models.

Windows group	1 (small)	2 (big)
width m	1.8	2.1
height m	1	1.9
area	1.8	3.99
WWR	25%	58%
Total windows per office	10	10

Table 2. Windows glazing specifications.

parameter	3-pane	4-pane
Solar heat gain coef. (SHGC)	0.46	0.37
T. Solar transmittance	0.39	0.32
Visible transmittance	0.9	0.9
Glazing U-value	0.61	0.32
Internal emissivity	0.89	0.89
External emissivity	0.89	0.89

Table 3 The climate data parameters that are constant for each month.

parameter	June	July	August	September
dry bulb min (°C)	14	14	14	14
dry bulb max (°C)	25	27	26.7	23
wet bulb max (°C)	19.2	19.2	19.2	19.2
wind speed (m/s)	3.8	3.8	3.8	3.8
wind direction (°)	40	40	40	40

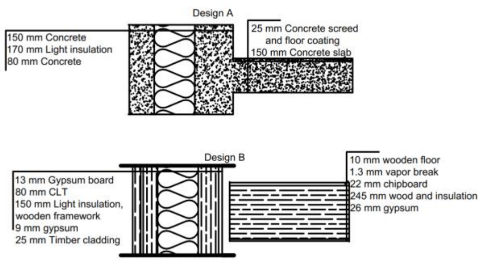

Figure 3. Structural design types of the case studies, Design A (high thermal mass) and Design B (low thermal mass).

Several assumptions have been made to facilitate the study. These assumptions were as follows:

- The number of occupants in each office was 10, the installed power of equipment and lighting was 12 W/m^2 and 6 W/m^2 respectively,
- The supply air temperature was 18 °C,
- The offices and the staircase had a Constant Air Volume flow of 1.4 l/(m^2*s),
- Shading of the windows was integrated internal blinds with sun control (never opened),
- Room temperature setpoint was 25°C,
- Internal walls were the same in both heavy and light construction Design types: 100mm of concrete, 30mm of light insulation and 50mm of gypsum with U-value 0.77 W/(m^2*K).

In the plan, there are four different offices with the dimensions 16m x 8m, having an area of 128 m^2. The height of the offices was 3m, which lead to 72m^2 of windowed walls. In the 3D views **Figure 4** and **Figure 5**, the sizes and arrangements of the windows can be seen.

The office building was on the middle floor of a building, which means that the model does not have a roof connecting to the ambient air or floor slab connecting to the soil.

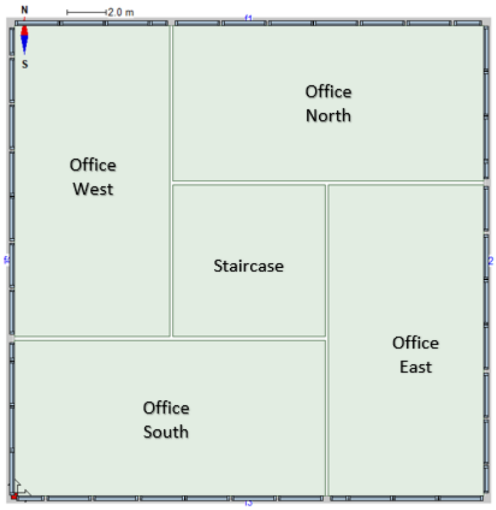

Figure 4. General office plan, 24.5m x 24.5m

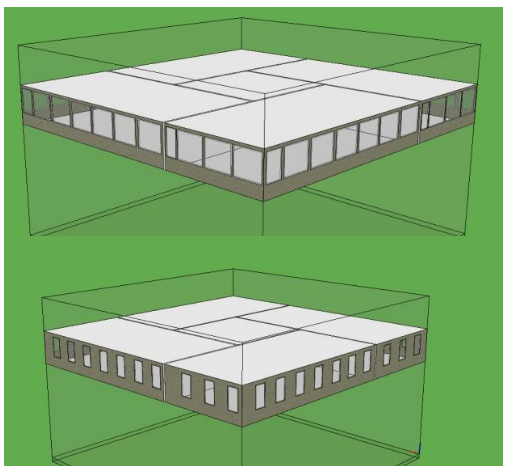

Figure 5 3d of the model with 2 different Window to Wall Ratio (WWR)

3 Results and Discussion

The analysis results are from simulations for a 4-month period from the 1st of June to the end of September, by using the schedules and profiles described in the previous sections. A heat balance chart from a warm week of the East office, when the profile derived from EM24 data was used, is shown in **Figure 6**. The building was modeled according to the design B (light construction) with big windows. This combination resulted in the highest cooling capacity needed among 80 possible combinations. From the heat balance chart, the reader can realize that the internal blinds of the windows are limiting the direct sunlight (yellow), but the heat from windows and absorbed heat in the internal blinds (light blue color with peaks) are the biggest contributors to the warm indoor air. The internal heat gains are the second contributors, then heat from occupants and equipment.

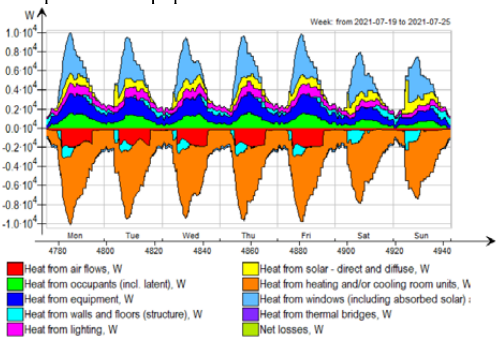

Figure 6 Heat Balance chart of a warm week for the East office, EM24 profile, light construction and big windows

A summary of all the simulations is shown in **Figure 7**. The South and East offices need a bigger cooling system per square meter compared to the Northern and Western offices. The effect of having a heavy structure (in this study, exposed interior concrete wall and floor) is positive, leading to lower cooling system size. The reason behind this reduction is the thermal mass of the building structure which works as a regulator of the indoor air temperature by keeping the coldness of the weather during less occupied hours and releasing it during the warm periods. The size of the windows is also influencing the results: the bigger the window, the bigger the size of the cooling system. From the heat balance chart, **Figure 6**, we see that the sun heat is controlled by using internal blinds, so the heat which transfers through windows became important, thus forcing the designers to choose bigger cooling systems.

The simulations based on the busy profile, EM24, resulted in much bigger cooling systems compared to average profiles from EM7 and the profiles from EN 16798-1. In practice, practitioners usually use a set of assumptions for occupancy and may use the suggestions of the EN 16798-1 standard. For busier offices that are overcrowded according to the original design, these assumptions and suggestions can become problematic, leading to either forced movements between offices or low users' satisfaction. On average, window size change from Window to Wall Ratio (WWR) 25% to 58% resulted in 35% bigger cooling systems; besides, having the thermal mass of the heavy structure in the zones can reduce the size of the cooling systems by 7% on average.

The differences between the size of the cooling system for different occupancy/equipment profiles for the Northern office are visible in **Figure 8**. The reader can see that the significance of differences among the results of the simulations with the EN 16798-1 suggested values depends on the profiles that are selected. While the difference is not significant if the results are compared to the average results of the EM profiles together, it is significant indeed compared to each individual profile. Since all three EM profiles are taken from the actual offices, it is important to consider such gaps and try to fill them when designing office buildings.

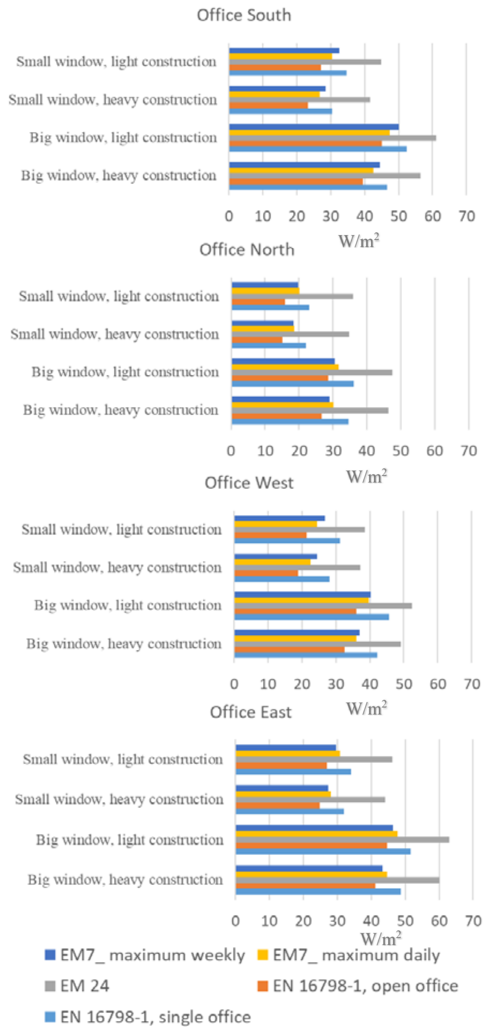

Figure 7 Cooling system size drawn using the results of the simulations for different scenarios/offices

As we can see in **Figure 7** and **Figure 8**, the profiles suggested by the EN 16798-1 standard are not satisfactory in some situations, Therefore the designers need to understand the functionality of the zones and predict the internal heat gains of different zones carefully. A thorough study on profiles can lead to specific profiles that can be suggested for specific offices in a defined location in the future.

We also should remark again that the present study concerns only a *zonal* analysis. At the full-building scale the assessment becomes more involved since the cooling demand is also linked with de-humidification of supply air flow rate while there is a potential to use Renewable Energy Sources (RES) to cover a part of the cooling demand.

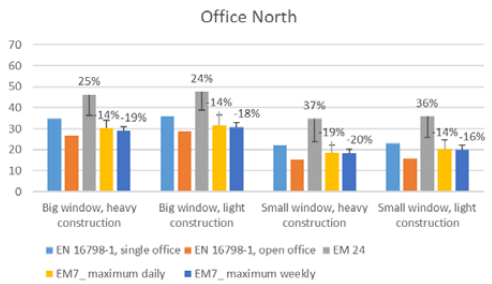

Figure 8 The cooling system size for the Northern office, magnifying the differences between profiles and EN 16798-1 suggestion.

Recalling our measured data, the blue line in **Figure 1** is the average consumption in the building. This line can be a good reference for dimensioning the cooling system of the whole building, while dimensioning the individual cooling devices in each zone needs a specific profile for that zone. Using the EN 16798-1 suggestion is good to start with, however being able to predict the profiles using smarter methods will lead to more efficient cooling device installation and cooling systems.

In this study, we calculated the total cooling demand of each zone. In reality, there is a huge potential in utilizing the free cooling concept in cold climates to reduce the cooling demand. This means that by using only the external air temperature, we will be able to cool the indoor environment down without consuming energy for cooling devices.

To do a brief sensitivity analysis, we decided to use the maximum cooling capacity sizes that were calculated using the EM7 profiles for simulating based on the EM24 profiles. A model is developed with constant cooling capacity for ideal coolers in 4 different offices derived from simulations of EM7 profiles, to report the mean temperature of the offices during the simulation period. The duration curve of the four offices is shown in **Figure 9**. From the figure, we can see that nearly one-third of the hours in the simulation period have a mean temperature higher than the set point. Detailed analysis and specific studies on such cases can be done in a separate paper in the future.

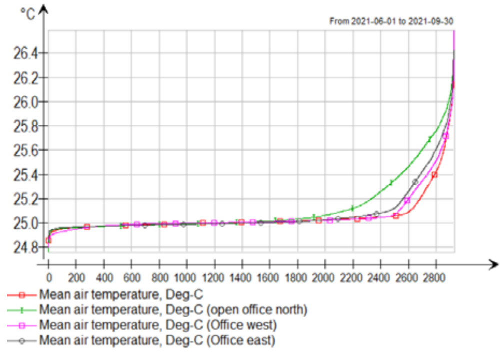

Figure 9 Duration Curve for 4 offices in a building with heavy construction, big windows and EM24 profile while the cooling capacity o ideal coolers are set to be equal to the designed values with EM7 profile.

4 Conclusion

Due to the climate change, the modeling of buildings for the warm periods and cooling system design are becoming more and more needed, especially in the Northern region of the EU. While nowadays designers are incorporating sustainable façade design which increases the internal heat gain impact on the cooling system, the results of this study show the importance of predicting the internal heat gains with as low margins as possible during the design stage. Having in mind the heat gain through windows is also another factor toward a successful cooling system design.

In the future, a more in-depth data analysis to suggest a better profile for the specific area than the standard EN 16798-1 can be a positive contribution, since such suggestions can be tested and compared to make the suggested profile even smoother.

The impact of thermal mass can be investigated in detail, using a profile with low occupancy and a profile with high occupancy, to check how much occupancy will make a difference in cooling system sizing.

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Artiklid

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