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Design optimization of an assisted living facility to improve summer thermal comfort in warming climates

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ABSTRACT

Assisted living facilities with optimal summer thermal comfort are necessary to ensure improved quality of life for the older individuals in warming climates. Older individuals are exposed to higher mortality risks during periods of excessive heat. This study aims to identify and optimize key design variables for a passive house certified assisted living facility in Belgium with high comfort expectations using EnergyPlus to improve indoor thermal comfort during extreme climates. The sensitivity analysis used the Standard Regression Coefficient method with Latin Hypercube Sampling for eighteen design variables under four categories: layout, envelope, operation, and system. The analysis identified flat roof and external floor insulation as the most influential parameters, whereas lighting gain and cooling setback temperature were the least influential parameters. Furthermore, optimizing the reference building with the most sensitive design variables using a genetic algorithm based on the NSGA-II method found ideal configurations that would ensure minimum thermal discomfort hours during extreme summers. The study findings provide an evidence-based approach for building engineers and designers for early-stage design of assisted living facilities that maintain optimal comfort in mixed humid climates of Europe.

1. Introduction

1.1. Study background

Climate change phenomena have exposed communities across the globe to more frequent and severe heat events like heat waves [1]. Buildings as an extensive infrastructure are considered an essential component of the resilience of communities against the impacts of heat waves [2]. The United Nations Environment Programme (UNEP) defines building resilience as "the ability of a building to meet the occupant's needs and provide for a safe, steady, and comfortable use in response to changing conditions outside" [3]. The health-related risk factors related to health, like heat stroke, dehydration [4], sleeplessness [5], etc., make the older inhabitants in assisted living facilities a particularly vulnerable group [6] during these extreme heat events. The proportion of older individuals over 65 is growing in the European Union (EU) due to demographic change [7]. The percentage of the population aged 65 years or over increased by 3% in the EU and 2.1% in Belgium between 2013 and 2023. The current trends indicate that there will be a significant increase in the percentage of the older individuals in the following decades. According to these estimates, the proportion of vulnerable

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people who require assisted care will also rise [8], and if the criteria for assisted living facility admission and the levels of home care are unchanged, the number of nursing home beds will require 50% more capacity by 2030 [9] to meet the increasing care demand. With the increasing rate of climate change, extreme heat events like heat waves are predicted to grow in frequency and intensity [10,11], adding to these concerns.

Age is often correlated with heat-related mortality in population-based studies [12]. Heat waves are often associated with higher mortality rates, especially among the older individuals [13] in nursing and care facilities [14]. Over 400 deaths were observed in this population group during August 2003 due to heat in Southwest Germany. People over 90 and needing higher additional care had a disproportionately high death rate during the heat wave [12]. The correlation between the mortality rates and maximum daily temperature [12] is shown in Fig. 1. The average mortality rate was 64% higher in the worst-case temperature than the best-case temperature level. These findings are supported by the results from [15] that found heat waves have an adverse effect on mortality in nursing homes and recommended more attention to the impacts of extreme heat events on assisted living facilities. The Impact of heat on the older individuals was also observed after Hurricane Irma in Florida in 2017, when a tree branch struck a power transformer and dislodged a fuse, cutting off the power to a two-story nursing home that claimed the lives of 12 residents due to heat stroke. According to government reports on the accident, the second-floor interior temperature reached 37.2 °C during the event and was the main contributor to the deaths [16].

Studies from [2] on the thermal performance of assisted living facilities suggested that even though the newly constructed facilities are energy efficient, heat will be trapped within, exposing the occupants to heat stress if natural ventilation is not included in the design. According to the study, there was a significant variation in thermal performance amongst resident bedrooms, depending on their location, orientation, and window area. Due to solar heat gains through the roof and windows, the south-facing bedrooms on the second story are exposed to the highest risk. The varying levels of thermal resilience across all bedrooms suggest that design and operating approaches for the most vulnerable bedrooms in assisted living facilities should be carefully considered. While assessing the performance of assisted living facilities against extreme heat events, extreme weather data should be used instead of typical meteorological year (TMY) data to evaluate measures for improving building resilience [17]. However, it is recommended that more case studies are essential to understand how energy efficiency and resilience of buildings interact to give practitioners and policymakers useful tools, best practices, and clear guidelines.

1.2. *Literature review*

Building optimization through sensitivity analysis is an important tool that is critical to ensure ideal thermal comfort while reducing operational energy use. A literature review of the most relevant studies that focus on building optimization for ideal performance is listed in Table 1. Global sensitivity analysis from Liu et al. [18] focused on the energy performance of heat recovery ventilation for zero-emission buildings and identified rotary heat recovery design as the most influential parameter for energy efficiency and savings in demand-controlled ventilation with heat recovery. A multi-stage sensitivity analysis and design approach for the optimization of zero/low energy buildings without heating in subtropics was proposed by Li et al. [19]. The study identified that the selection of key parameters was highly influenced by winter thermal discomfort. Zhao et al. [20] provided key design variables for high and low-rise buildings considering the building morphology and climate. The study identified overhangs and skylights as the most influential parameters besides wall thermal absorptance, which was ignored in previous studies.

In Prataviera et al. [22], urban building energy models were used as simulation tools for building energy use estimation, and the study proposed an uncertainty analysis for improving energy needs and a sensitivity analysis to identify the key design variables. A sensitivity analysis approach for prefabricated houses was introduced by Naji et al. [26], which used hierarchical cluster analysis to identify the most sensitive envelope parameters against degree days for different groups of cities with similar sensitivities. The

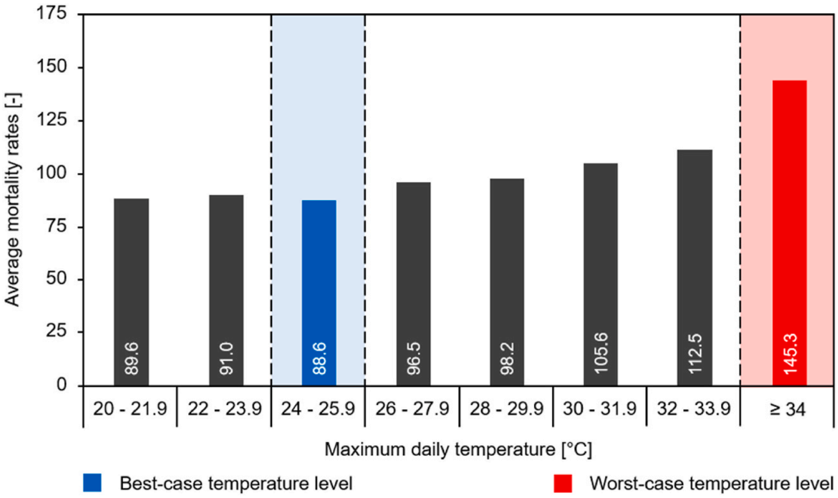


Fig. 1. Average mortality rates per 100,000 people in assisted living facilities with respect to maximum daily temperature levels [12].

Table 1
A summary of existing studies focusing on sensitivity analysis for multi-parameter building optimization.

Location and climate zone [21]	Study method	Building type	HVAC system	Sensitivity analysis	Number of parameters	Study focus	Reference
Milan (4A) and Verona (4A), Italy	Modeling using EUReCA	Residential and commercial buildings	Typical HVAC systems	Sensitivity analysis with regression method	9	Energy use	Prataviera et al. [22]
Hong Kong (2A), China	Modeling using TRNSYS and MATLAB	Net zero-energy office building	Chiller with constant speed fan-coil units and water pumps	Global sensitivity analysis with SRC method	24	Energy use	Zhang et al. [23]
Hong Kong (2A), China	Modeling using EnergyPlus and MATLAB	Multipurpose zero-energy building	Ideal air-conditioning system with infinite cooling capacity	Global sensitivity analysis with regression method, Morris method, and FAST method	29	Thermal comfort Energy use	Li et al. [19]
Dublin (5A), Ireland	Modeling using EnergyPlus	2-story and 1-story detached, 2-story semi-detached dwellings, mid-floor and top-floor apartments	Ideal load air system	Global sensitivity analysis with Morris and Sobol method	24	Energy use	Neale et al. [24]
Oslo (6A), Norway	Modeling using simulations Observational using testing box	Office building	Demand-controlled ventilation with heat recovery	Global sensitivity analysis with Sobol method	11	Energy use	Liu et al. [18]
Toronto (5A) and (6A), Ottawa (6A), Vancouver (4C), and Edmonton (7), Canada	Modeling using EnergyPlus and MATLAB	Office buildings	Single centralized heating and cooling plant	Sensitivity analysis	8	Thermal comfort Energy use	Gunay et al. [25]
Multiple study locations across different climate zones in Australia	Modeling using TRNSYS, jEPlus, and SimLab	Prefabricated house	Thermal conditioning using setpoint temperatures	Global sensitivity analysis with regression method	35	Energy use	Naji et al. [26]
Multiple study locations across different climate zones in China	Modeling using EnergyPlus, JEPlus, and SimLab	High-rise and low-rise office buildings	Mechanical ventilation, air-conditioning, and heating systems	Global sensitivity analysis with Morris method	35	Thermal discomfort Energy use	Zhao et al. [20]

sensitivity analysis from Neale et al. [24] compared the Morris and Sobol technique and found that these methods provided similar sensitivity rankings for various key parameters. Studies from Zhang et al. [23] used a similar global sensitivity analysis with the Standardized Regression Coefficient (SRC) method to identify key parameters for net zero-energy building grid interactions to develop a computation-efficient optimization approach. Studies from Gunay et al. [25] determined ventilation rates and schedules as the key parameters for building optimization.

The primary findings from [19] considering annual energy use and winter thermal discomfort in the reference residential building in Hong Kong observed optimal values of 0.11 for window solar gain coefficient, 0.25 for window-to-wall ratio (WWR), 0.86 for wall solar absorptance, 0.24 for overhang projection ratio, 6° for building orientation, and 0.1 for roof solar absorptance. Similar variations in key design variables were observed in [26], where window glazing, and solar shading were most influential for prefabricated house across various climate zones in Australia. However, window variables had a higher impact in cooling dominated climates, whereas wall insulation was more influential in heating dominated climates. In line with this study [20], observed variation in influential envelope parameters for energy use depending on the number of building stories. Overhang variables like tilt angle and depth as fraction of height was the key design variable for high rise buildings. On the contrary, it was skylight variables like solar heat gain coefficient, skylight to roof ratio, and u-value for low-rise buildings. The study results from existing literature in Table 1 show that key design variable will vary depending on the building types, sensitivity analysis objectives, study location, and climate zone. Therefore, it is significant to optimize the reference assisted living facility located near Brussels, in a mixed humid climate for improved summer thermal comfort.

1.3. Knowledge gaps and relevance

The analysis of recent literature indicated the following missing aspects. Most existing studies are performed for residential or office buildings, and there is limited literature on vulnerable buildings like assisted living facilities in mixed humid climates. In addition, the sensitive design variables affecting a building's performance vary for the building type and climate zones [20]. From the existing literature, it is important to consider the reliability of the developed building simulation model as these models have several input parameters, and each one affects the building's thermal performance in a particular way. As a result, identifying the specific influential parameters will make the building performance more efficient [24]. The study's relevance is based on the fact that the key design variables for ideal summer thermal comfort in assisted living facilities cannot be determined from these existing state-of-the-art studies. The quality of life of vulnerable populations like the older individuals depends on thermal comfort in assisted living facilities during extreme climates, which adds to the study's relevance. Although the occurrence of extreme climates is statistically rare, studies from [27] have indicated that the frequency and intensity of extreme heat events like heat waves that were considered unlikely before 1986 have increased by ten times and three times in recent periods. Moreover, a systematic review of recent literature by [28] points out the vulnerability of older individuals during extreme heat events like heat waves and the need for action plans to protect them. These factors contribute to the rationale of optimizing assisted living facilities during extreme climates, considering the vulnerability of their inhabitants.

1.4. Objectives and novelty

Through comprehensive modeling and analysis, the study aims to bridge the existing knowledge gaps by identifying: a. key design variables for optimal summer thermal comfort in the reference assisted living facility, and b. optimal configurations to minimize the indoor discomfort hours in the reference assisted living facility. The study's main novelty is that it uses a replicable analysis approach optimizing a vulnerable building for ideal thermal performance for extreme climate scenarios that practitioners and researchers can use for future projects and case studies. Using the SRC with Latin Hypercube Sampling (LHS), the sensitivity analysis assessed 18 building parameters that affect assisted living facility performance in mixed humid climates. The assisted living facility was optimized by prioritizing minimal indoor discomfort hours using the influential design variables. Implementing the proposed study approach will result in more reliable decision support during the early design stages of assisted living facilities, thereby providing a guideline for future research and practice. To the author's knowledge, this is the first study that identified the key design variables for optimal thermal performance in assisted living facilities for extreme climates in mixed humid zones.

2. Methodology

The relevant information on the case study, like the weather data, location, geometry, floor plans, HVAC systems, materials, operation schedules, energy bills, etc., was collected for creating an energy performance simulation model as in [24]. The model was created using DesignBuilder v7.0.1, a user-friendly graphical user interface for the EnergyPlus v9.6.0 simulation engine [29,30]. Building thermal loads are determined by EnergyPlus using the heat balance approach. This approach accounts for all heat balances on exterior and interior surfaces and instantaneous heat transfer through the building. At each time step, the heat transfer through conduction, convection, and radiation is estimated in EnergyPlus [31]. The building performance simulations frequently include estimates and simplifications, which do not always accurately reflect reality. The confidence level in the model's output is constrained by this input uncertainty, meaning that simulation model results could be incorrect. These errors are measured using uncertainty analysis [32].

2.1. Model analysis

A global sensitivity analysis with SRC [23] with LHS [33] to identify key design variables is used as a precursor to optimizing the assisted living facility. The P-values show the confidence or statistical significance in the SRC calculated for each variable and should ideally be less than 0.05, in which case they are shown in green. Confidence in the SRC value of each variable depends on the p-value [34]. The SRC value determines the significance of the input variable on output performance. Higher the absolute value of SRC, the higher its significance on the output performance [23]. Additionally, positive SRC value indicates that as the input variable increases, output performance increases. On the contrary, a negative SRC value indicates that output performance decreases as the input variable increases. Additionally, LHS is an effective sampling method for the population mean to be accurately modeled. For the mean values of the samples to be close to the mean value of the requested distribution range, it is generally recommended that a sample size of ten times the number of design variables is used [35]. LHS method is used for sampling the design variables and to quantify the response uncertainty using less number of simulations. This is achieved using a stratified sampling scheme used by LHS [36]. The LHS process produces samples that accurately reflect the underlying distribution. A set of 570 iterations is used in this study, more than the generally recommended sample size for accurate results.

SRC method is one of the method with lower data requirements and simpler execution compared to other analysis methods [37,38]. SRC method uses performance outputs (y) and input variables (x) to create a linear multivariate model as shown in equation (1) [23].

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_m x_m \tag{1}$$

where β_k (k = 1, 2, ……,m) represent regression coefficient calculated using least squares method [39]. SRC values are further calculated using regression coefficient as shown in equation (2) [23].

$$SRC_k = \frac{\beta_k \sigma_{xk}}{\sigma_y} \tag{2}$$

where σ_{xk} is the standard deviation of input variable (x_k), and σ_y is the standards deviation of performance output (y).

Once the most sensitive parameters are identified, the building is optimized, and individual solutions suited for the optimal thermal performance of the assisted living facility are identified. Optimization analysis of the assisted living facility is performed using a genetic algorithm based on the NSGA-II method [34,40,41]. According to [42], NSGA-II algorithm uses an elitist principle and explicit diversity preserving mechanism that emphasizes on non-dominated solutions. When p and q are two samples in a population P, p dominates q if p is superior to q in at least one of the objectives and p is not worse than q in the rest of the objectives. NSGA-II uses this concept of dominance to assess each sample of its population. By using this method, the algorithm can identify which samples are the fittest and calculate the distance between each sample by crowding distance-sorting algorithm [43]. Here, NSGA-II algorithm is run for a dual-objective optimization of the reference assisted living facility. The main objective of performing optimization analysis is to improve thermal comfort and minimize cooling energy consumption in the reference assisted living facility. NSGA-II algorithm was run for 30 generations, with a population size of 20. To analyze the trade-off between the degree of discomfort and energy use provided by design, hours of discomfort and cooling energy use are used as outputs. The total number of iterations ran for optimization was 618. The algorithm sorts out and discards some iterations crowded-sorting mechanism, which is explained in [42]. The population is driven towards the pareto-optimal front by the operators of the NSGA-II operators with each generation. This multi-objective method optimization using DesignBuilder [44,45] offers a good trade-off among well-distributed and well-converged solution sets and is highly effective at ranking competing objectives. The analysis results will indicate the options with the least discomfort hours and minimal energy use.

2.2. Application on a reference building

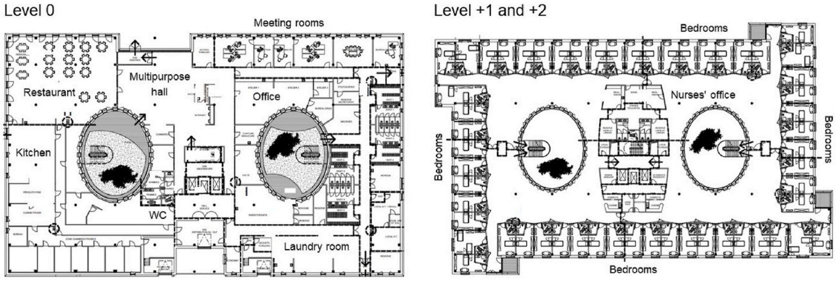
2.2.1. Assisted living facility

The reference assisted living facility is a 3-story building in the countryside of Tournai in Belgium. It is located at the coordinates of 50.64° N, 3.38° E. It comprises multiple building spaces, including personal areas like bedrooms, common areas like meeting rooms, restaurants, kitchens, a multipurpose hall, and circulation areas like corridors. It has 102 single bedrooms and 10 double bedrooms to accommodate 122 senior citizens. It is a passive house [46] certified building with an infiltration rate at 50 pa of less than 0.6 ac/h, and a lighting energy demand of less than 8 W/m^2. It is included in comfort category I, which has the most stringent comfort thresholds per

a. Exterior view

b. Energy performance simulation model

c. Floor plans



d. Thermal zones

Fig. 2. Illustration of the reference case study: a. assisted living facility, b. energy performance simulation model, c. floor plans, and d. thermal zoning [48].

EN 16798-1 [47]. The assisted living facility has a total floor area of 8000 m^2. The building is well-insulated. The windows are triple-glazed with a WWR of 30%, and the south façade has external blinds that operate automatically during high temperatures.

The building areas are served by a centralized variable air volume (VAV) system. The single and double bedrooms are designed for an airflow of 100 m^3/h and 150 m^3/h [48]. The airflow is reduced at night due to noise issues. The building is conditioned using 4 air-to-water heat pumps with a power rating of 80 kW. These heat pumps are installed on the roof and operate in pairs. The roof also includes photovoltaic panels for electricity and solar thermal panels for water heating. It is a low-energy building constructed in 2016 in compliance with Passive House standards [46] that recommends a heating and cooling energy use of less than 15 kWh/m^2.a, while maintaining the indoor temperature at a constant value of 24 °C ± 0.5 °C throughout the year per Agence Wallonne pour une Vie de Qualite (AViQ) recommendations [48] considering the thermal sensitivity of the older individuals. Additionally, the reference assisted living facility is part of Public Centre for Social Welfare (CPAS), which includes numerous other assisted living facilities across Belgium [49]. This makes the case study unique as the learned lessons from the reference assisted living facility could be used to improve thermal comfort in existing buildings and new constructions.

The assisted living facility with the simulation model, floor plans, and thermal zones [47] are shown in Fig. 2. The envelope characteristics of the reference assisted living facility are listed in Table 2. The energy simulation model was calibrated for indices like Normalized Mean Bias Error (NMBE) and Coefficient of the Variation of the Root Mean Square Error CV(RMSE) within the thresholds of 5% and 15% as recommended by ASHRAE Guideline 14 [50]. The calibration of electricity use gave an NMBE of 1.7% and CV (RMSE) of 5.9%, whereas the calibration of natural gas usage gave an NMBE of 3.9 % and CV(RMSE) of 13.7% [48]. The energy simulation model is run from May to September to include the summer months from June to August, with May and September as shoulder months [51]. More information on building operational details and the assisted living facility energy performance simulation model is available for open access [52].

2.2.2. *Input variables*

The list of input design variables used for the sensitivity analysis in the paper is given in Table 3. These parameters were chosen based on the review of studies from Table 1. A set of 18 design variables specific to the layout, envelope, operation, and system are evaluated using sensitivity analysis [53]. The parameters of high significance are then selected for the optimization analysis. The uncertainty analysis, sensitivity analysis, and optimization are performed by prioritizing indoor discomfort hours, calculated based on ASHRAE 55 discomfort hours for summer clothing [54]. This is because the building is an EN 16798-1 category I building with high thermal comfort expectations [47].

2.2.3. *Climate data*

The climate model used for the baseline model simulation is the Modele Atmospherique Regional (MAR) v3.11.4 [55]. The MAR has a geographical resolution of 5 km over an integration region of 120 × 90 grid cells centered over Belgium to produce hourly meteorological outputs [56]. Building performance in this study is evaluated using the Extreme Meteorological Year (XMY) data set from 2021 to 2040. The XMYs are hourly-based synthetic years constructed from outlier months [57], representing extreme weather scenarios. The Finkelstein-Schafer statistics [58] compare each month's distribution within the long-term distribution with a minimum of 20 years of that month for the available observations or modeled data. There are numerous ways to create weather files. However, the weather files for this study are created according to the ISO 15927-4 [59] guidelines and are briefly explained in [56]. The XMY file

Table 2
Envelope characteristics of the reference assisted living facility used in the study.

Envelope	Layers	Materials used	Thickness [m]	Thermal transmittance [W/m^2K]
Ground floor	Outer	Urea-formaldehyde foam	0.1327	0.250
	Third	Cast concrete	0.1000	
	Second	Floor screed	0.0700	
	Inner	Timber flooring	0.0300	
Internal floor	Outer	0.25 Linoleum/cork tile	0.0064	2.273
	Inner	Concrete reinforced	0.2000	
External floor	Outer	External rendering	0.0250	0.250
	Second	MW stone wool	0.1182	
	Inner	Timber flooring	0.0050	
External roof	Outer	Asphalt	0.0100	0.250
	Third	MW glass wool	0.1445	
	Second	Air gap	0.2000	
	Inner	Plasterboard	0.0130	
External wall	Outer	Brickwork	0.1000	0.350
	Third	XPS extruded polystyrene	0.0795	
	Second	Concrete block	0.1000	
	Inner	Gypsum plastering	0.0130	
Internal partition	Outer	Gypsum plasterboard	0.0250	1.639
	Second	Air gap	0.1000	
	Inner	Gypsum plasterboard	0.0250	
Doors	External	Painted oak	0.0350	2.823
	Internal	Painted oak	0.0350	2.823
Windows	External	SageGlass climatop blue no tint	30% WWR	0.687

Table 3
The input design variables for sensitivity analysis in the reference assisted living facility.

Code	Input parameter	Unit	Minimum	Maximum	Increment	Steps	Distribution
Layout parameters							
P01	Site orientation	°	0	315	45	8	Discrete
P02	Window-to-wall ratio	%	20	60	10	5	Discrete
P03	Glazing type	–	Dbl Clr 3mm/13 mm Air, Dbl Clr 6mm/13 mm Air, SageGlass Climatop blue no tint, Trp Clr 3mm/13 mm Air			4	Discrete
P04	Local shading	–	No shading, Louvres (1 m), Overhangs (1 m)			3	Discrete
Envelope parameters							
P05	External wall insulation	M	0.02	0.14	0.03	5	Discrete
P06	Flat roof insulation	M	0.08	0.20	0.03	5	Discrete
P07	Ground floor insulation	M	0.07	0.19	0.03	5	Discrete
P08	External floor insulation	M	0.09	0.21	0.03	5	Discrete
P09	Internal partition insulation	M	0.04	0.16	0.03	5	Discrete
P10	Airtightness	ac/h	0.40	0.80	0.10	5	Discrete
Operational parameters							
P11	Mechanical ventilation rate	l/s-pers	8	20			Continuous
P12	Internal equipment gains	W/m^2	8	20			Continuous
P13	Lighting gains	W/m^2	4	12			Continuous
P14	Occupancy density	Pers/m^2	0.01	0.03			Continuous
System parameters							
P15	Cooling setpoint	°C	24	28			Continuous
P16	Cooling setback	°C	36	44			Continuous
P17	Heating setpoint	°C	19	23			Continuous
P18	Heating setback	°C	10	18			Continuous

Ground floor: Floor between basement and occupied zones, Internal floors: Floors between occupied zones, External floor: Floor adjacent to external air.

from 2021 to 2040 for SSP 5 represents the weather scenario as the reference assisted living facility is an EN 16798-1 category I [47] vulnerable building, evaluating the building performance for the worst-case scenarios was important to account for extreme heat conditions. All the weather files used in this study are freely available in open source [60]. The hourly variations and statistical data for air temperature [°C], relative humidity [%], solar radiation [kWh/m^2], and wind speed [m/s] for the 2030s_SSP5 XMY file from Brussels are shown in Fig. 3.

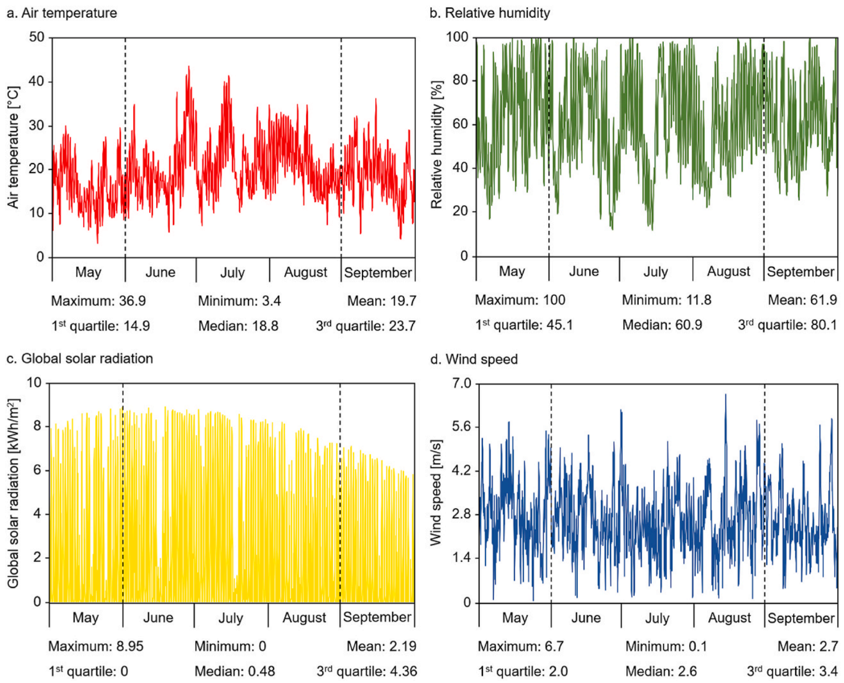


Fig. 3. Hourly variation in outdoor weather parameters from May to September for 2030s_SSP5 XMY file from Brussels: a. air temperature [°C], b. relative humidity [%], c. global solar radiation [Wh/m^2], and d. wind speed [m/s].

3. Results

This study was based on a single output objective of indoor discomfort hours based on ASHRAE 55 for summer clothing [54]. The uncertainty analysis results indicate the extent of indoor discomfort hours in the reference assisted living facility during extreme climate scenarios due to the variations of the input design variables. These variations and statistical parameters are shown in Fig. 4. 570 iterations were performed for different input design variable levels. The values are consistent with the range and distribution profile listed in Table 3. The discomfort hours varied from a minimum of 239 h to a maximum of 268 h during the monitored period from May 01 to September 30. Mean and median values of 251 h and 252 h were recorded, respectively.

Indoor discomfort hours [h] are strongly influenced by flat roof insulation. However, there is a reverse link. An increase in flat roof insulation leads to a decrease in indoor discomfort hours [h]. Indoor discomfort hours [h] are also strongly influenced by external floor insulation [m], ground floor insulation [m], internal partition insulation [m], internal equipment gains [W/m^2] and site orientation [°]. Other parameters evaluated do not noticeably influence indoor discomfort hours [h]. Therefore, these entries may be ignored for further optimization analysis of the model. The standardized regression coefficient, which indicates the relative sensitivity of the input variable to indoor discomfort hours and the p-value that indicates the statistical significance of the input variables are shown in Fig. 5. The adjusted R-squared value for the model was 0.91, which shows that the regression can justify the output with high precision [34]. The impacts of high-significance variables on the reference assisted living facility are as follows.

a. The variation in flat roof insulation thickness, from 0.08 to 0.20 m, with an increment of 0.03 m, has the most significant impact. The analysis, with a p-value of 0, indicates a high level of significance. An observed SRC value of −0.76 suggests that increasing flat roof insulation thickness will decrease indoor discomfort hours.
b. External floor insulation thickness is varied from 0.09 to 0.21 m with an increment of 0.03 m. A significant p-value of 0 indicates a high level of confidence, while an SRC value of −0.41 indicates that indoor discomfort hours decreases with an increase in external floor insulation thickness.
c. The variation in ground floor insulation thickness is from 0.07 to 0.19 m, with an increment of 0.03 m. A p-value of 0 and an SRC value of 0.31 were observed, that indicates an increase in indoor discomfort hours with increased ground floor insulation thickness.
d. Internal partition insulation thickness varies from 0.04 to 0.16 m, with an increment of 0.03 m. The analysis observed a significant p-value of 0 and an SRC of −0.18. This points to a decrease in indoor discomfort hours with an increase in internal partition thickness.
e. Internal equipment gains vary from 8 to 20 kWh/m2 with a continuous distribution. The results indicate a positive correlation with an SRC of 0.14 and a significant p-value of 0. An increase in internal equipment gain will increase the indoor discomfort hours.
f. Site orientation is selected using variations from 0 to 315° relative to the north with an increment of 45°. The results indicate a significant p-value of 0 and an SRC of 0.09. Increasing the site orientation angle relative to the north will increase indoor discomfort hours.

The key design variables considered are flat roof insulation (FRI), external floor insulation (EFI), ground floor insulation (GFI), internal partition insulation (IPI), internal equipment gains (IEG), and site orientation (SO). Different configurations of design variables of high significance for various levels of indoor discomfort hours [h] and cooling energy use [kWh] are listed in Fig. 6. From building optimization, configurations with low indoor discomfort hours [h] (C01 and C02) are identified. During the optimization, indoor discomfort hours varied between 241 h and 270 h. The cooling energy use varied between 4461 kWh and 4576 kWh. The statistically important values for indoor discomfort hours [h] and cooling energy use [kWh] are listed in Table 4.

Table 5 lists the configurations with low indoor discomfort hours [h]. C01 is the best optimized configuration and C02 is second best optimized configuration. The csv file of optimization was exported from EnergyPlus for analysis. During the analysis, the ground

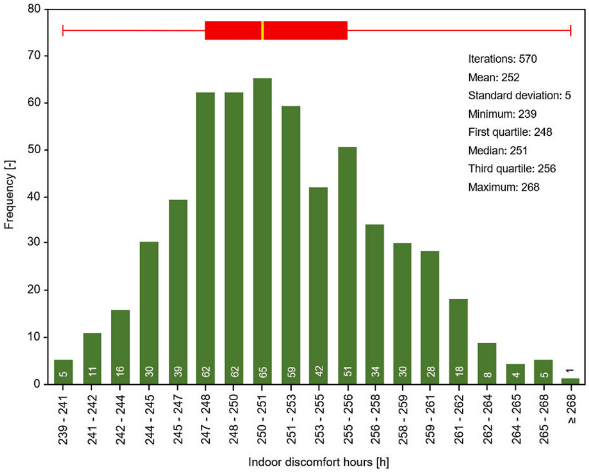


Fig. 4. Uncertainty analysis results for indoor discomfort hours [h] using various design variables in the reference assisted living facility.

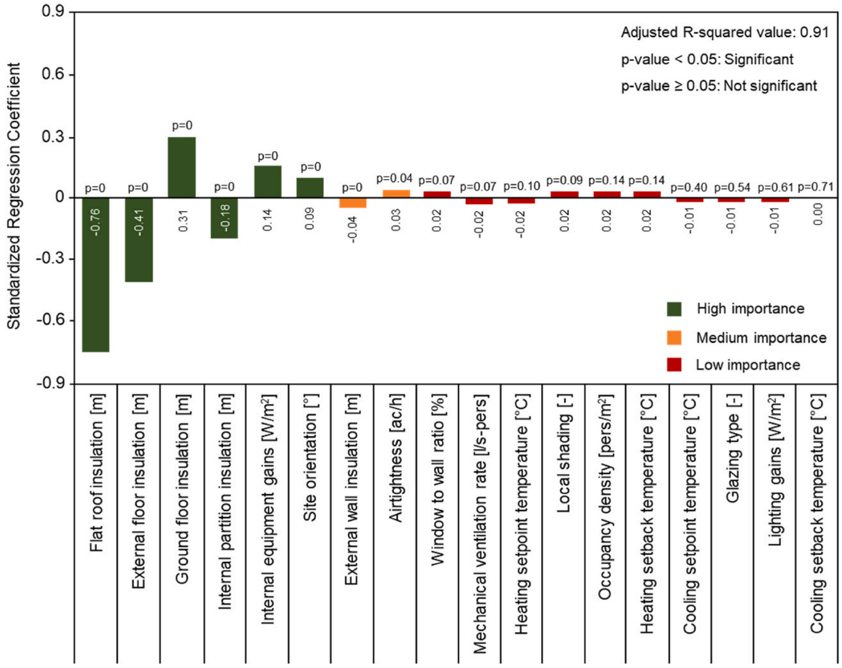


Fig. 5. Sensitivity analysis results with high, medium, and low significance design variables for indoor discomfort hours [h] in the reference assisted living facility.

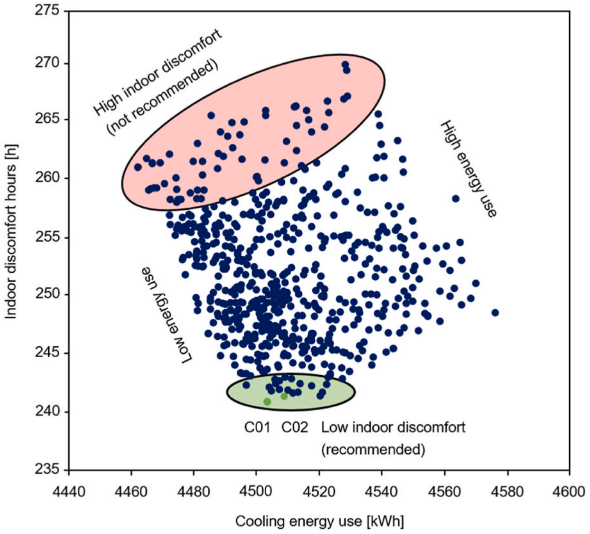


Fig. 6. Design optimization with the significant variables for minimal indoor discomfort hours [h] in the reference assisted living facility.

Table 4
Statistical analysis of building optimization results for indoor discomfort hours [h] and cooling energy use [kWh].

Values	Indoor discomfort hours [h]	Cooling energy use [kWh]
Average	252	4508
Standard deviation	6	22
Minimum	241	4461
First quartile	248	4493
Median	252	4505
Third quartile	256	4523
Maximum	270	4576

Table 5

Optimized configurations for minimal indoor discomfort hours [h] and cooling energy use [kWh] in the reference assisted living facility.

No.	Indoor discomfort hours [h]	Cooling energy use [kWh]	Most sensitive design variables					
			FRI [m]	EFI [m]	GFI [m]	IPI [m]	IEG [W/m^2]	SO [°]
Low indoor discomfort hours [h] – Recommended configurations								
C01	241	4503	0.20	0.21	0.07	0.16	8.50	240
C02	242	4508	0.20	0.21	0.07	0.16	11.0	230

floor and internal partition insulation levels remained at values of 0.07 m and 0.16 m. The internal equipment gain was 8.50 W/m^2 for C01, while it was higher for C02 at 11 kWh/m^2. The site orientation also showed 10° variations relative to the north for these configurations. The flat roof insulation and external floor insulation were 0.20 m and 0.21 m for C01 and C02. In addition to sensitivity analysis, this forms a second line of evidence that flat roof insulation and external floor insulation have the highest influence on thermal comfort in the reference assisted living facility.

4. Discussions

This study used a whole building energy performance simulation model for an assisted living facility in Belgium. The model was calibrated based on monthly energy use data as in [48]. Sensitivity analysis of the selected input design variables from existing literature in Table 1 was performed to identify the influential design variables that impact indoor discomfort hours [h]. In total, 18 input design variables were identified for sensitivity analysis using SRC with LHS. The sensitivity analysis focused on only one objective, indoor discomfort hours [h] for summer clothing, based on ASHRAE 55 [54], since it is an EN 16798-1 category I building with high comfort expectations [47]. The adjusted R-squared value of 0.91 indicates a high confidence level of the model evaluated. The results showed that indoor discomfort hours can be minimized by choosing appropriate envelope characteristics like roof and floor insulation levels. The main takeaways from the study are discussed below.

4.1. Main findings

The SRC values indicate that increasing envelope variables like the insulation of the flat roof (P06) with a SRC of −0.76, external floor (P08) with a SRC of −0.41, and internal partitions (P09) with a SRC of −0.18 decrease indoor discomfort, whereas increasing ground floor insulation (P07) with a SRC of 0.31 will increase indoor discomfort. Operational variables like internal equipment gains (P12) with a SRC of 0.14 and layout variables like site orientation (P01) with a SRC of 0.09 are also directly related to indoor discomfort. The other design variables, like external wall insulation (P05) with a SRC of −0.04, airtightness (P10) with a SRC of 0.03 etc., had no significant impact on the indoor discomfort hours and were not considered for further optimization of the reference assisted living facility. The optimization of the building model with the most sensitive variables identified multiple optimal configurations that ensured minimum indoor discomfort and cooling energy use.

Multiple configurations for building performance considering thermal comfort and cooling energy use are identified here. Configuration C01, with the lowest indoor discomfort, is recommended for assisted living facilities as it is classified as EN 16798-1 category I building with high comfort expectations [47]. The lowest indoor discomfort was recorded at 241 h for configuration C01 with insulation levels of 0.20 m for the flat roof (U-value: 0.182 W/m^{2}k), 0.21 m for the external floor (U-value: 0.182 W/m^{2}k), 0.07 m for the ground floor (U-value: 0.416 W/m^{2}k), 0.16 m for the internal partition (U-value: 1.639 W/m^{2}k), 8.50 kWh/m^2 of internal equipment gain, and 240° site orientation relative to north. The ideal thermal environment in assisted living facilities during extreme climates in Belgium can be ensured by properly implementing flat roof insulation, external floor insulation, ground floor insulation, internal partition insulation, internal equipment gains, and site orientation. Increasing the insulation thickness of the flat roof, external floor, and internal partitions and decreasing the insulation thickness of the ground floor will improve indoor thermal comfort.

4.2. Design recommendations

It is recommended that designers and engineers should assess the building performance under extreme meteorological scenarios rather than typical meteorological scenarios. This will improve the climate-proof design of buildings that can adapt and mitigate the worst impacts of changing climate while ensuring optimal energy efficiency. Envelope characteristics like insulation levels should be given priority during the early design stages. While evaluating the building performance of EN 16798-1 category I buildings [47], like assisted living facilities, indoor thermal comfort must be prioritized over energy performance since these facilities house the older individuals who are vulnerable to cardiovascular and respiratory syndromes [61,62]. The older individuals have low adaptability towards thermal extremes in the indoor environment [12], so assisted living facilities should have high comfort levels. Additionally, among the design variables, flat roof insulation had the most impact on comfort, with increased insulation levels decreasing the indoor discomfort hours [h]. The benefits of passive strategies like cool roofs [63,64], green roofs [65,66], and roof ponds [67,68] in limiting thermal transmittance through roofs should be assessed during the early design stages.

4.3. Strengths and limitations

The main strengths of this study are that a simulation-based method was used to evaluate a calibrated whole building energy performance model [69,70], considering the layout, envelope, operational, and system parameters as input variables and building discomfort hours as the output variable. As a result of calibration according to ASHRAE Guideline 14 [50], the model outputs and building performance are more consistent with real-world scenarios. Additionally, while answering various questions about thermal discomfort in assisted living facilities in Brussels, this study provides practical retrofit solutions for future renovations in similar climates in cities like Paris, London, Amsterdam, etc. The main limitation of this study is that it represents a specific building and climate zone, so building designers should generally conduct a sensitivity analysis based on their unique case study and its boundary conditions. However, the study methodology offered an effective tool for assessing thermal discomfort in assisted living facilities through sensitivity analysis using SRC with LHS and selecting the design variables from existing literature from Table 1. To the best of the author's knowledge, this is the first attempt to study the key design variables for assisted living facilities in mixed humid climates.

4.4. Implications for practice and research

This study provides important insights that will contribute to guidelines from AViQ [71] in Belgium to ensure ideal thermal comfort in assisted living facilities during extreme climates. These findings will guide the early-stage design process to ensure the health and well-being of the older individuals in these facilities. These recommendations will also support AViQ's mission to promote the quality of life of the older individuals living in its facilities across Wallonia. The population aged 65 years or over increased by 3% in Europe and 2.1% in Belgium from 2013 to 2023 [7,72]. By the end of the century in 2100, the older individuals will likely make up a larger proportion of the total population in the European Union, with people 65 or over will make up 31.3% of the population, up from 21.1% in 2022 [72]. With this rapid increase in the aging population, there will be a need for capacity expansion in assisted living facilities while ensuring ideal indoor thermal comfort. To build new assisted living facilities and renovate existing ones in Belgium, it is necessary to investigate the best design options and incorporate the key design variables while considering the local climate [73]. The next step must materialize these evidence-based design solutions from the study into real building elements and components using locally available materials, methods, and solutions [74].

5. Conclusions

A design approach combining global sensitivity analysis and optimization is proposed to design assisted living facilities in the mixed humid climates of Belgium. The study was focused on the whole building energy performance simulation model of a real-world assisted living facility calibrated using monthly energy use values. The building parameters were collected from the building management and recreated using EnergyPlus simulation software. The global sensitivity analysis was carried out using SRC with the LHS to systematically examine the effects of 18 design variables for optimal thermal performance. Identifying the key design variables using global sensitivity analysis reduced the optimization of unnecessary or non-critical parameters. Once the most influential design variables were identified, a comprehensive optimization was defined using a genetic algorithm based on the NSGA-II method for thermal discomfort hours [h] and cooling energy use [kWh/m^2]. The uncertainty analysis of the reference model showed that the indoor discomfort hours [h] varied from 239 h to 268 h in the assisted living facility during extreme climate scenarios. Further, optimizing the assisted living facility with the most sensitive design variables provided configuration C01 with the lowest indoor discomfort hours of 241 h. However, C01 would produce high cooling energy use of 4503 kWh as a consequence.

The main significance of the study is that it provides a simulation-based approach to support reliable decision-making during the early design stages of assisted living facilities, thereby providing a guideline for future research and practice. Additionally, this is one of the first such attempts to identify and optimize critical design variables for optimal thermal performance in assisted living facilities during extreme climates in mixed humid climate zones. Moreover, building designers and engineers should consider evaluating the building performance under extreme climate scenarios. Although statistically rare, excessive heat during extreme climates can have deteriorating effects on the quality of life for older individuals and increase the risk of morbidity and mortality. Additionally, growing urbanization will contribute to urban heat islands that will further exacerbate short-term and long-term effects of climate change on built environments. Therefore, climate-proofing assisted living facilities that house vulnerable communities like older individuals for improved well-being in extreme climates should be prioritized.

However, further research is required to assess the nexus between thermal comfort, thermal resilience, and energy use. While improving the insulation level will improve summer thermal comfort in the assisted living facility, its long-term impact on energy savings, peak load demands, greenhouse gas emissions, etc., must also be assessed. We limited our current study to thermal comfort as the building is an EN 16798-1 category I building with high thermal comfort expectations. The future work will also evaluate critical design variables that affect the building performance, especially in Belgium's high-density urban areas, which will be considered for improved indoor thermal comfort during extreme weather scenarios. Future building codes and standards should consider the nexus between thermal comfort, resilience, and building energy use. These policy changes are essential to develop resilient and healthy assisted living facilities that are energy efficient. Undoubtedly, these new policy changes would call for understanding and acceptance from the facility management and staff, as well as the residents and their families [75].

CRediT authorship contribution statement

Deepak Amaripadath: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Deo Prasad:** Writing – review & editing, Validation, Methodology. **Taha Osman Safi:** Visualization, Validation, Software. **Shady Attia:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

Declaration of competing interest

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Data availability

Data will be made available on request.

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