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Overheating Risk Analysis in Long-Term Care Homes—Development of Overheating Limit Criteria

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Abstract: Climate heat waves occurring in urban centers are a serious threat to public health and wellbeing. Historically, most heat-related mortalities have arisen from excessive overheating of building interiors housing older occupants. This paper developed an approach that combines the results from building simulation and bioheat models to generate health-based limit criteria for overheating in long-term care homes (LTCHs) by which the body dehydration and core temperature of older residents are capped during overheating events. The models of the LTCHs were created for buildings representative of old and current construction practices for selected Canadian locations. The models were calibrated using measurements of indoor temperature and humidity acquired from monitoring the building interiors and the use of published building energy use intensity data. A general procedure to identify overheating events and quantify their attributes in terms of duration, intensity, and severity was developed and applied to LTCHs to generate the limit criteria. Comparing the limit criteria from the proposed and comfort-based methods showed evident differences. The proposed method predicted the overheating risk consistent with the overall thermal comfort during overheating events in contrast to the comfort-based methods. The new limit criteria are intended to be used in any study to evaluate overheating risk in similar buildings.

Keywords: overheating; thermal comfort; older people; long-term care home; nursing home; building; heat wave; extreme heat; climate change

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1. Introduction

Global warming has become a fact, being felt in every place around the world, and is projected to worsen and intensify in the future [1]. Extreme heat events (or heat waves) arising from such global warming have been identified as a serious threat to global public health and wellbeing. Historical heat waves have caused a high toll on the world population in terms of mortality and morbidity [2]. Global statistics indicate that approximately 0.489 million people have died annually from heat waves over the last two decades [3]. Most (>98%) heat-related deaths occurred in building interiors due to the fact of excessive space overheating, and the most affected occupants were older (over 65 years) people with compromised health or living alone [4–6]. Institutional long-term care homes (LTCHs) were among the hard-hit buildings. Older occupants of LTCHs are the most vulnerable to heat due to the combined effects of their age-weakened physiology, chronic health challenges, and cognitive impairment. As similar or worse extreme heat events are expected to occur in the future, combined with the ever-increasing Canadian old population (expected to reach 25% of the total population in 2050, a 64% increase from the old population in 2020 [7]), prevention of overheating risk in particularly vulnerable buildings such as LTCHs is much needed than ever to protect the health of building occupants.

In Canada, LTCHs (also called nursing homes, continuing care facilities, and residential care homes) are regulated by provinces, and there are currently 2076 homes with

198,220 beds, most of them are in Ontario (30% homes; 39.8% beds), Quebec (21% homes; 20.6% beds), and British Columbia (14.8% homes; 13.8% beds) [8]. LTCHs may take various shapes, but the layouts that utilize wing designs, such as an L-shape with short corridors for frail elderly residents and amenities grouped together work the best [9]. An LTCH provides on-the-hour (24 h/day) continuous support services to older residents, including nursing services and personal care support services. Older residents above the age of 65 years represent approximately 93.4% or higher, and the vast majority (>90%) of them have chronic illnesses or some form of cognitive impairment [10,11]. In addition to older residents, LTCH occupants include administration staff, medical personnel, personal care support staff, and others (for housekeeping, food preparation, etc. [12]). The interior spaces of LTCHs are arranged to include private and common spaces. Private spaces include resident bedrooms with one or more occupants, offices, and nursing rooms; the common spaces accessible by everyone include circulation halls, food preparation, and serving areas, lounges, entertainment or activities areas, and areas for religious services [13]. This mixture of occupant types, activity levels, and space functions represents a challenge to provide thermal comfort for everybody and manage the risk of space overheating [14]. Furthermore, the aforementioned health and physical challenges limit the adaptation of older residents to changing indoor climates, putting them at higher risk of outdoor extreme heat events [15].

Historical heat waves around the world have shown that older people in LCTHs and other senior buildings were the first to succumb to outdoor heat events [4–6]. During the European heat wave in 2003, approximately 15,000 heat-related deaths occurred in France, among which 33.3% of the deaths occurred in LTCHs [16]. In Finland, the mortality rate during the heat waves of the summer periods of 2000–2014 was 8% in social care facilities and 76% in healthcare facilities [17]. In England, the proportion of deaths in LTCHs was 21% during the heat waves in the summer period (June to September) of 2020 [18]. In Canada, the recent 2021 summer heat dome in British Columbia resulted in 619 excess deaths over a week of extremely high temperatures soaring to 49.6 °C. The proportion of deaths in senior and long-term homes was 7% [6]. Similarly, the 2010 and 2018 summer heat waves in Montreal island (Quebec) resulted in 106 and 66 excess deaths, respectively, among which 11.3 and 7.2% occurred in LTCHs [4,19,20].

Recognizing this imminent threat of extreme heat events on human health, thermal comfort, and space overheating studies in LTCHs have received increasing attention in recent years. Guerra and Tweed [14] conducted a field study in a passive house care home in the UK and focused on thermal comfort surveys for the various types of building occupants, except older residents (not being able to answer the questionnaire). The study found that the staff were not comfortable and considered the building to be too warm in the summer. However, when they were asked about the comfort of the older residents, they reported that residents were comfortable in all spaces. Gupta et al. [15] conducted field monitoring of indoor conditions and staff interviews in four long-term care buildings in the UK during the cool summer period (June to September) of 2015. The overheating risk was evaluated using the CIBSE TM59 criteria [21]. All bedrooms were evaluated for sleep comfort using the static threshold temperature of 26 °C despite some of them being fully (24 h) occupied, and the common lounge areas and offices were evaluated using both the adaptive and static comfort criteria. Almost all bedrooms were found to be overheated, and three out of eight lounges were overheated using the adaptive approach. The study lacked thermal comfort data to benchmark the overheating findings. The authors questioned the appropriateness of the application of adaptive thermal comfort to older residents having limitations for thermal adaptation. Wang et al. [22] conducted concurrent field indoor temperature measurement and thermal comfort surveys in 19 long-term care buildings with 1040 residents aged 70 years and above during winter, spring, and summer in Shanghai, China. The indoor temperature varied from 12.4 to 29.7 °C with a corresponding range of outdoor temperature between 3.8 and 29.3 °C. The seasonal summer neutral temperature was 25.1 °C, and its daily value varied from 12.4 to 29.7 °C as a function of the outdoor running mean temperature. These neutral temperatures were distinctively higher than the Chinese non-older people. Hughes et al. [23] conducted a field monitoring study and thermal comfort in 37 naturally ventilated senior homes in the southwest UK during the summers (June–September) of 2017 and 2018. The summer average outdoor temperatures were 15.5 and 17.1 °C, respectively, and the corresponding mean internal temperatures were 21.2 and 23.3 °C. An overheating risk analysis was carried out using the CIBSE TM59 [21]. The study found that neither the PMV model nor the adaptive model of ISO 15251 [24] accurately predicted thermal sensation votes in the houses. The occupants were broadly (89 to 91%) comfortable during both summers. However, more than 50% of the monitored spaces (living rooms and bedrooms) were significantly overheated during the warmer summer of 2018. Gupta et al. [25,26] conducted field monitoring and thermal comfort studies in the summer period of 2019 in two old (18th century) and new (2013) care homes in London (UK). Simulation studies were also conducted to explore the building responses under future climate projections. The outdoor temperatures during the monitoring period peaked at 35 °C at both sites. The corresponding indoor temperatures peaked at 34.7 °C in the old home and 32.5 °C in the new home. In both care homes, temperatures remained in the 24–28 °C range for the majority of the time and did not fall below 20 °C. Overheating was evaluated with four sets of criteria from CIBSE Guide A [27], CIBSE TM52 [28], CIBSE TM59 [21], and Public Health England [29]. The majority of the monitored spaces of both care homes were found to overheat regardless of the metrics used. However, thermal comfort data indicated that 25–38% and 35–42% of the staff responses perceived indoor temperatures to be neutral and uncomfortably hot, respectively, versus 43–63% and 13–19% for the older residents, indicating that older residents preferred warmer temperatures than the staffs. In fact, the median temperature for the neutral thermal sensation was 29.5 °C for older residents and 28 °C for the staff.

The aforementioned field studies in long-term care and senior homes reiterate that older people have distinct thermal comfort requirements, which cannot be fully answered using existing static and adaptive comfort models. Furthermore, further work is needed to consolidate the relationships between thermal comfort in the field and heat-related health effects with the overheating limit criteria. The goal of this paper is two-fold: (1) to develop new health-based overheating limit criteria to help protect the health of older residents in long-term care settings during extreme heat events; (2) to compare the new criteria with existing comfort-based criteria to explore the possibility of having a common background to benchmark various types of overheating criteria. The paper is structured as follows. After the brief literature review in the introduction section, the methodology describes the details of the procedure to generate the overheating limit criteria using calibrated building simulation. The results section outlines the obtained limit criteria and their comparison with existing comfort-based criteria. In the discussion section, the findings and application of the study are elaborated to benefit the simulation community, and the study limitations are identified. Finally, the conclusion summarizes the general methodology and findings and presents future work.

2. Methodology

The methodology used computer simulation to develop overheating limit criteria in LTCHs to cover different Canadian climate zones. It consists of two main steps: (1) the development of calibrated building models of LTCH; (2) the development of a procedure to evaluate the risk of overheating and obtain limit criteria. Following are the details of the methodology used in this study.

2.1. Representative Building Models

The representative building models of LTCHs to analyze the overheating risk are built based on the geometry and orientation of a real monitored building, with construction details taken as typical averages for the construction practice at the selected locality and year of construction. Two sets of models were created for old and new buildings in five selected

Canadian cities covering typical Canadian climate zones, including zone 6 (Montreal, QC; Ottawa, ON), zone 5 (Toronto, ON), zone 4 (Vancouver, BC), and zone 7A (Calgary, AB). The National Energy Code of Canada for Buildings [30] classifies the climate zones based on the annual heating degree days (HDDs) with a reference temperature of 18 °C. The HDD ranges for the selected climate zones are zone 4 (<3000); zone 5 (3000 to 3999); zone 6 (4000 to 4999); and zone 7A (5000 to 6999). Humidity (or rain precipitation) is, however, not considered for the climate zone classification. The summer of the Vancouver coastal climate is typically cool and humid. The summers of Montreal, Ottawa, and Toronto are similar, typically continental warm and humid, but Toronto is more humid as moderated by Lake Ontario. The summer in Calgary is typically cool and less moist. The construction practice in the 1980s is selected for the old buildings, and newly built buildings conform to the requirements of the current national energy code of buildings (NECB-2017 [30]). Furthermore, old buildings are assumed to be partially retrofitted, for which the roofs are retrofitted to conform to NECB-2011 [31], and the lighting and mechanical systems and equipment are retrofitted to the requirements of NECB-2017. Walls and windows of old buildings are kept typical of the 1980 construction practice. The air infiltration data of the whole building with old and new constructions are taken as average values as reported in [32] or other publications of similar buildings and to produce typical energy use intensity data of similar buildings as published by Natural Resources Canada. Below are details on each model.

2.1.1. Building Geometry

The geometry of the representative building model is taken from the real geometry of a monitored long-term care building. The monitored building is L-shaped, as shown in Figure 1, with a total length and width of 44 and 42 m, respectively. The building is composed of five floors above the ground and a below-grade basement. On the first floor, there are hallway spaces, lounge area, food preparation area, resident bedrooms, and offices. The building has stairways and elevator shafts connecting the building floors. The second to fifth floors have similar layouts, with each floor composed of lounge area, bedrooms, and offices. The resident bedrooms are a mixture of private single bedrooms with bathrooms and semi-private double bedrooms sharing a common bathroom. The typical size of a single private bedroom is 5.4 × 3.6 m. The building can accommodate 96 residents. From the site visits and architectural plans of the building, the windows of the bedrooms are operable with a maximum opening area of 10% (for security reasons). The total window-to-wall ratio is calculated to be 14.13%.

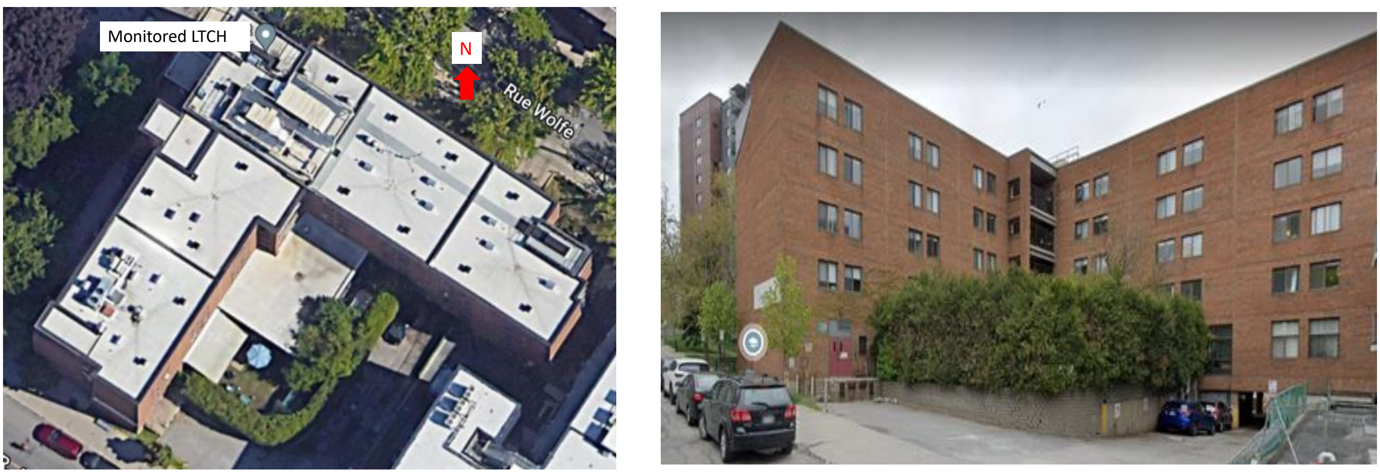

Figure 1. Shape and orientation of the monitored LTCH: aerial view (**left**) and south-east and south-west facades (**right**).

2.1.2. Building Construction

The envelope construction data for the representative building models for the retrofitted old (1980) and new (2017) constructions were taken from the applicable building energy codes and publications on similar buildings. Table 1 summarizes the building characteristics of the old and new building models. The air leakage data of the whole building were taken as average values (covering years from 1975 to 1995 for old constructions and years above 2010 for new constructions) of published data of similar multi-unit residential buildings as reported in [32].

Table 1. Construction details of the old and new building models.

Construction	Old (1980) with Partial Retrofit	New (2017)
Air infiltration rate [32] ACH@75Pa (liters/s/m^2)	4.31 (4.35)	2.16 (2.17)
Basement floor	Insulated slab (U-factor = 0.331 W/m^2 K): 100 mm foam Insulation (exterior); 100 mm concrete slab; 70 mm screed; 30 mm timber flooring (interior)	
Walls	Concrete block (U-factor = 0.557 W/m^2 K) [33,34]: 100 mm brick veneer (exterior); 25 mm air space; 38 mm EPS insulation; 100 mm concrete block; 13 mm gypsum board (interior)	Steel stud (EPS insulation thickness varies with location; Table 2) [30]:100 mm brick veneer (exterior); 25 mm air space; EPS insulation; 13 mm OBS; 150 mm batt steel stud; 13 mm gypsum board (interior)
Roofs	Concrete deck (XPS insulation thickness varies with location; Table 2): 1 mm membrane (exterior); XPS insulation; 150 mm concrete slab; 13 mm gypsum board (interior)	
Windows (WWR = 14.13%)	Double clear glass with aluminum frame (COG U-factor = 2.7 W/ m^2 K)	Double clear low-E glass with argon gas fill and aluminum frame (COG U-factor = 1.33 W/ m^2 K)
Exterior doors	Oak; U-factor = 3 W/m^2 K	
Solar shading	Internal vertical blinds with manual control applied only to bedrooms and offices	

Table 2. Operation schedules and internal heat gains.

Space	Schedule *	Occupancy Density (m^2/Person)	Lighting Power Density (W/m^2)	Equipment Power Density (W/m^2)
Bedrooms	J	25	6.7	2.5
Offices	B	20	10	7.5
Lounge	B	10	8.4	1
Food areas	B	20	11.4	10
Corridor	B	100	7.1	0
Stairwell	B	200	6.3	0
Elevators	B	0	7.3	0
Mechanical room	Always-ON	0	4.6	1

* Details of the operation schedules may be found in NECB 2017 [30].

2.1.3. Internal Casual Heat Gains

The internal casual heat gains include those from the lighting system, equipment, and occupants. The lighting system and equipment of the model with old constructions are assumed to be retrofitted to the current requirement of NECB 2017. Table 2 summarizes the power densities and operation schedules of internal casual heat gains.

2.1.4. Building HVAC System

Electrical baseboard heating is applied to all thermal zones of both building models with old and new constructions. The cooling and ventilation systems for both models are, however, different. For the old building models, a constant air volume (with continuous operation) central ventilation system with heat recovery is applied to the common lounge spaces of each floor (as in the monitored building) to provide the required minimum outdoor air according to ASHRAE 62.1-2022 [35], and individual packaged terminal air conditioners are applied to all building thermal zones, including bedrooms, lounges, offices, corridors, and food areas. For the new building models, five central packaged rooftop units supply the cooling and ventilation needs of all thermal zones of each floor. The rooftop unit consists of heat recovery unit, outdoor air mixing box, direct expansion cooling coil, electric heating coil (not activated), and variable air volume (VAV) supply fan. The VAV fan is operated on a continuous basis to supply the required minimum flow rate of outdoor air to the served zones. Exhaust fans are used as well in each bathroom of bedrooms and food areas. The fans are assumed to operate continuously with flow rates of 10 L/s (20 CFM) for bathrooms [36] and 3.5 L/s/m^2 for the food preparation areas (equivalent to 40 L/s or 80 CFM).

2.1.5. Building Thermal Zoning

The private bedrooms, semiprivate bedrooms (sharing a common bathroom), offices, food areas, and lounges are each treated as single thermal zones. The lounge spaces are open to the corridor spaces through fictitious internal windows (holes). The corridor and hall spaces are divided into three (left, center, and right) main thermal zones connected to each other by fictitious internal windows (holes). The stairwells and elevator shafts are divided into vertically stacked thermal zones, connected to each other by horizontal fictitious windows. All internal doors of each thermal zone are assumed closed to comply with the requirement of building fire codes, except those subject to occupant behavior, namely, those for bedrooms and offices. Windows of the common spaces are assumed not operable. Figures 2–4 show three-dimensional views and thermal zones of each floor of the building.

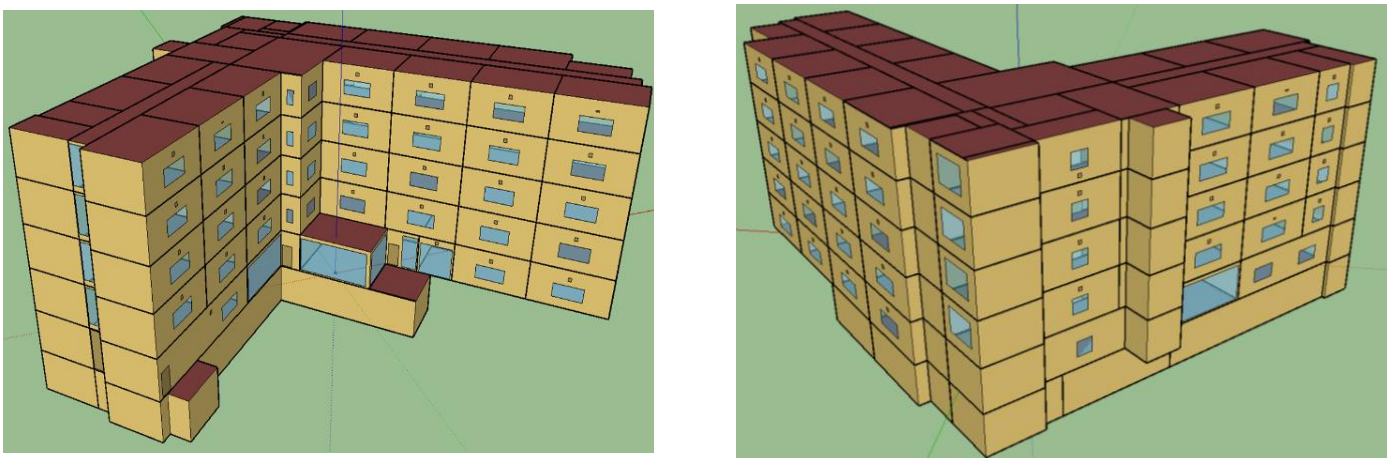

Figure 2. Three-dimensional views of the LTCH model—south (**left**) and north (**right**) facades.

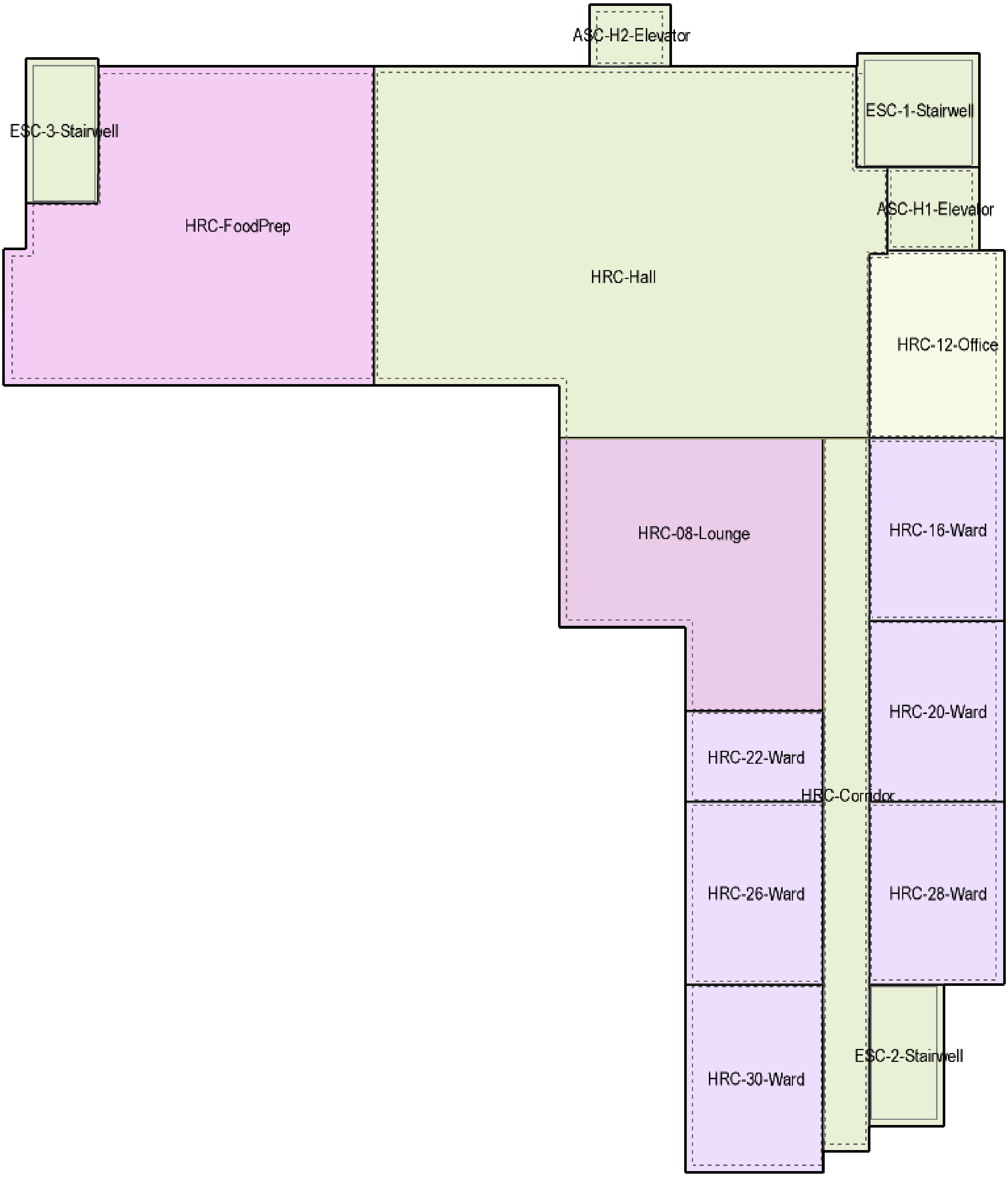

Figure 3. Thermal zones of floor 1.

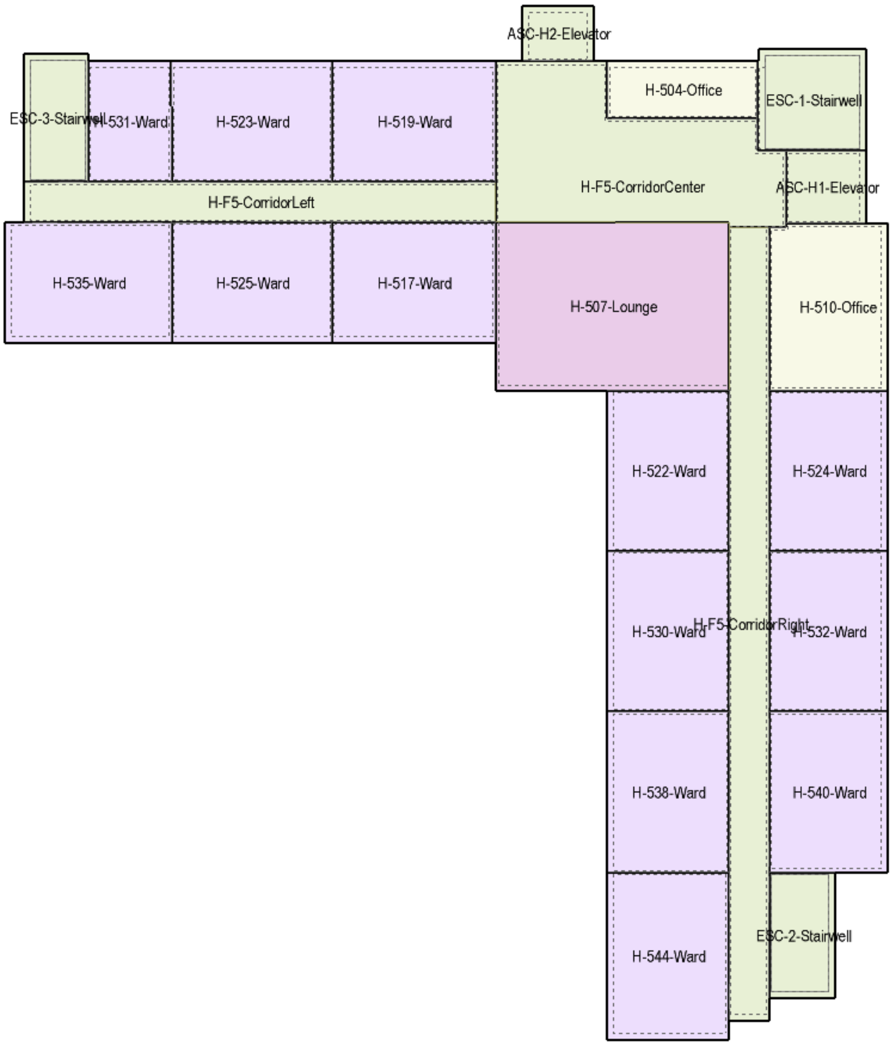

Figure 4. Thermal zones of floors 2 to 5.

2.2. Airflow Network Model

The airflow network model of the EnergyPlus software (v9.6; [37]) is applied to the representative building models to couple the outdoor environment, natural ventilation through intentional openings, and air infiltration with the indoor thermal simulation. The following assumptions were used to develop the network model:

1. Under the free running mode, resident bedrooms and offices w naturally ventilated subject to occupant behavior for the opening of operable windows and internal doors. From the site visits of the monitored building, the opening factor of the resident bedroom windows is restricted to 10%. Furthermore, due to the resident-free movement in the common spaces of the building, internal doors of bedrooms leading to the common corridor spaces are assumed to be opened on average by up to 50% (note that opening by more than 25% does not induce any significant changes in indoor temperature). The windows and internal doors of bedrooms and offices are opened if the indoor temperature exceeds the outdoor temperature and occupants start to feel thermal discomfort; otherwise, they are closed. Occupant behavior and thermal discomfort perception to open windows or doors may vary from one occupant to another. However, in this study, the average perception of thermal discomfort from all occupants was used and, therefore, two set point temperatures (for older and young adults) to open windows/doors were applied to all bedrooms and offices. Older (age > 65 years) people usually prefer warmer temperatures to obtain the same comfort level as young (average age) people [38,39]. According to the new comfort

model for older people by Laouadi [40], average older people (having a metabolic rate of 20% lower than young adults) in a sedentary position and wearing typical summer clothing (0.5 clo.) in still air (air velocity < 0.1 m/s) with a relative humidity of 45%, the indoor temperature for which older people start to feel thermal discomfort (PMV = 0.5) is 28.8 °C. This is very close to 29 °C, as reported in the field study in [25]. However, the set point for office occupants (young adults) was fixed at 26 °C. If air-conditioning was used in bedrooms and offices, all their windows and internal doors were assumed closed.

2. Windows of stairwells, food preparation areas, and lounges were non-operable.
3. Internal doors of stairwells and elevators were always closed to comply with the building fire code.
4. The air leakage data through the external and internal closed doors were taken as average values from the published study [41].
5. Whole building air leakage data were converted to exterior envelope surface leakage data assuming a uniform surface leakage distribution.

Based on these assumptions, the airflow network was composed of the following main components:

1. Leakage through the external building surfaces (walls, roofs, exterior doors, and non-operable windows), which were treated as crack leakages with mass flow coefficients calculated based on the typical whole building air leakage rate (Table 1);
2. Leakage through the external operable windows (treated automatically in EnergyPlus).
3. Leakage through horizontal openings connecting hollow thermal zones, such as stairwells and elevator shafts (treated automatically).
4. Leakage through the internal doors connecting building spaces of bedrooms, offices, food areas, stairwells, elevators, and corridors. The leakage data of these components were taken from the databases in [41].
5. Exhaust fans in bedrooms and food areas were linked to the airflow network.

2.3. Calibration of Building Models

The representative building models were calibrated using the field data of the monitored building and published energy use intensity (EUI) data of similar Canadian buildings.

For the model calibration using the field data, the general model of LTCHs with old construction was set-up to mimic the monitored building based on the known construction data collected during the site visits and surveys. The unknown input data of the monitored building, such as the internal heat gains, whole building leakage rate, and others, were, however, kept equal to the typical or average values of the general LTCH model. This approach was opted for in this study rather than adjusting these unknown inputs to minimize the error between the measured indoor conditions and simulations for three main reasons among many. First, the space usage (e.g., occupancy, lighting, equipment, operation of doors, windows, and shading) of the monitored building, except the limited monitored spaces, were not known, and therefore they have to be assumed. Second, the limited monitored spaces were not sufficient to adjust the many unknown input parameters (Tables 1 and 2) of the building and avoid any unrealistic combinations of parameter values that would result from an optimization calibration procedure. For example, the optimization procedure would not capture the true value of the building air infiltration rate (driven by wind and stack effect) due to the weak (negligible) stack effect in summer and the dominance of natural ventilation. Third, to obtain the order of magnitude on how realistic the indoor conditions are, as predicted by a general building model with typical/average input data, compared with real buildings. Indoor conditions are very important for overheating risk analysis, and any over- or underestimation will affect the interpretation of the results.

2.3.1. Field-Monitored Data

The real building in Figure 1 was monitored in the summer of 2020 to study overheating. Indoor sensors were installed in seven bedrooms and one lounge room to monitor the air temperature and relative humidity. All the sensors were installed in the same locations in each bedroom at the height of 1.7 m near the corner. Among the monitored bedrooms, three of them on the 5th floor (R523, R531, and R535) were naturally ventilated, and the remaining ones (R223, R235, R525, and R544) were air conditioned using window air-conditioners. The lounge space on the fifth floor was air-conditioned using a portable air conditioner. An outdoor weather station was installed on the roof of the building to monitor the air temperature, relative humidity, wind speed, and solar radiation. The monitored data were collected every five minutes and presented in hourly averages from 14 July 2020 to 3 August 2020. More details on the monitoring procedure may be found in the study [42]. For building simulation purposes, the non-monitored bedrooms and offices of the building were assumed to be naturally ventilated during the monitoring period.

The LTCH model for old construction was set-up to mimic the monitored building as mentioned before. The building location was set to Montreal (latitude = 45.51°; longitude = 73.58° W). The U-factors of the roof and walls are fixed to 0.445 and 0.557 W/m^{2}K, respectively. External shadings from neighboring buildings and trees were, however, not accounted for in the model.

Figure 5 compares the measured and simulated values of the indoor temperatures of the naturally ventilated bedrooms (R523, R531, and R535) and their average value. The building model predicted very well the trend of the bedroom temperature, with some fluctuation from bedroom to bedroom. The greatest difference between the simulated and measured values (<3 °C) occurred at approximately midnight (12:00 a.m.) for bedroom R523, and the lowest difference occurred for bedroom R531, followed by R535. This difference could be, among other factors, attributed to the occupant behavior towards window opening. For example, if occupants close windows and/or internal doors during nighttime before going to sleep, the indoor temperature will increase. Furthermore, occupants may use different (higher) threshold temperatures to open windows/doors, or may not opt to open windows/doors if they have some mobility issues. These factors were not accounted for in the simulation. Overall, the simulations showed a very good agreement with the measured data for the average temperature of the three bedrooms.

Figure 6 compares the measured and simulated values of the indoor relative humidity (RH) of the three naturally ventilated rooms and their average values. Both the simulation and measurement showed that the indoor RH was mainly affected by the outdoor RH, indicating the occurrence of natural ventilation in these spaces. The simulation predicted very well the daily trend of RH, with some overestimation of RH during nighttime. The overestimation of RH at nighttime was mainly due to the underestimation of the indoor temperature, as explained before. Overall, the simulations showed a very good agreement with the measured data for the average RH of the three bedrooms.

Table 3 lists the values of the root mean square error (RMSE) and mean bias error (MBE) of temperature and relative humidity calculated for each bedroom space and their average value. These error metrics are adopted in ASHRAE Guideline 14 [43] for building energy and water consumption. The positive values of MBE indicate that the simulations were generally higher than the measurement and vice versa for the negative values of MBE. At a room level, the RMSE-T varied from 0.9 to 1.7 °C with a room average value of 1 °C. The corresponding MBE-T is within −3 to 2%. The MBE-T range is within the accuracy limit of ±10% of ASHRAE [43], and the RMSE-T for the room average value is within the accuracy limit of 1.5 °C, as recommended by O'Donovan et al. [44] for the prediction of indoor temperature in naturally ventilated buildings. The prediction accuracy for the relative humidity was slightly lower than temperature, with an average RMSE-RH of 8% units and MBE-RH of 13%.

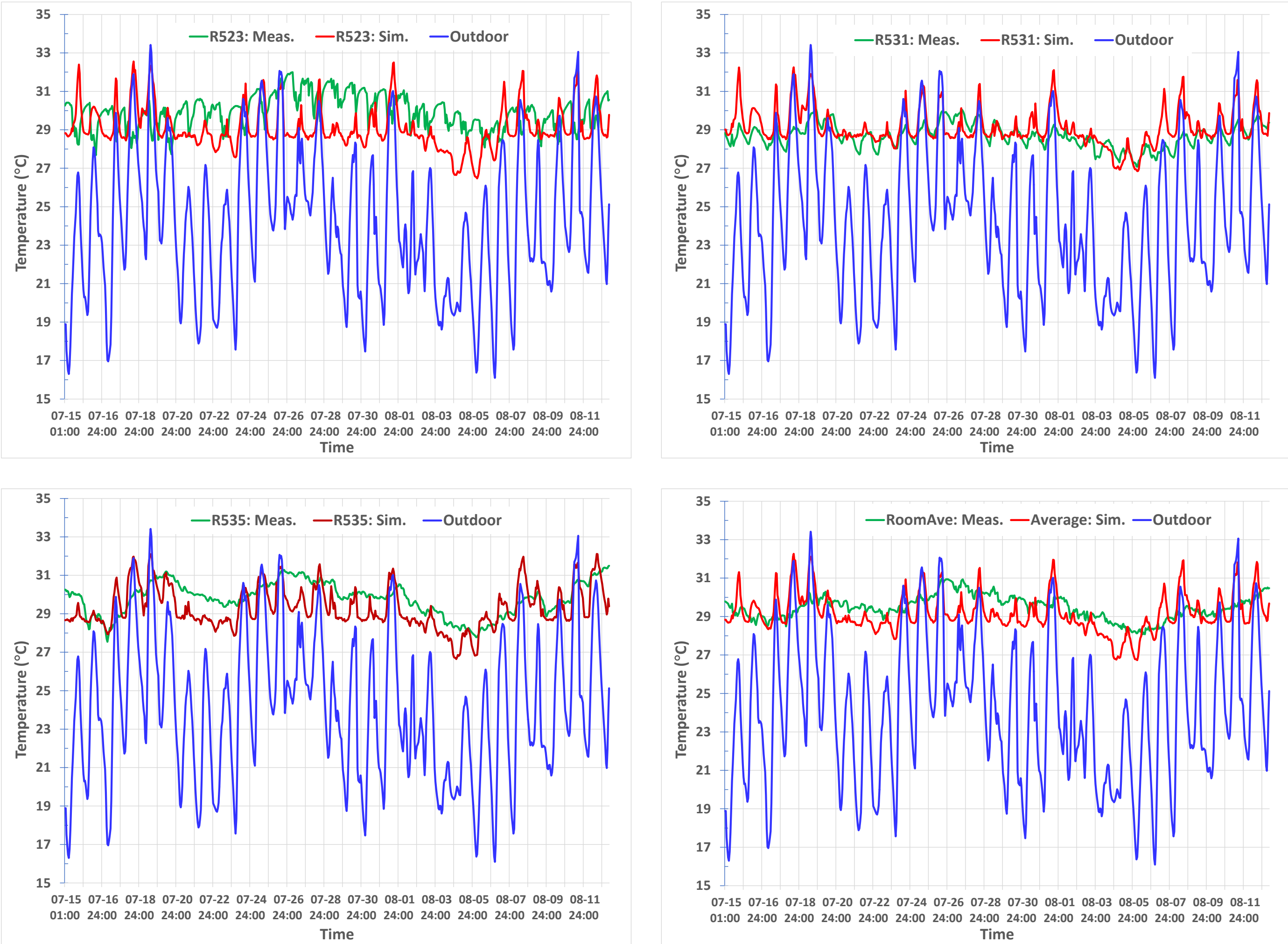

Figure 5. Comparison of indoor temperatures of bedrooms (R523, R531, and R535) and their average value.

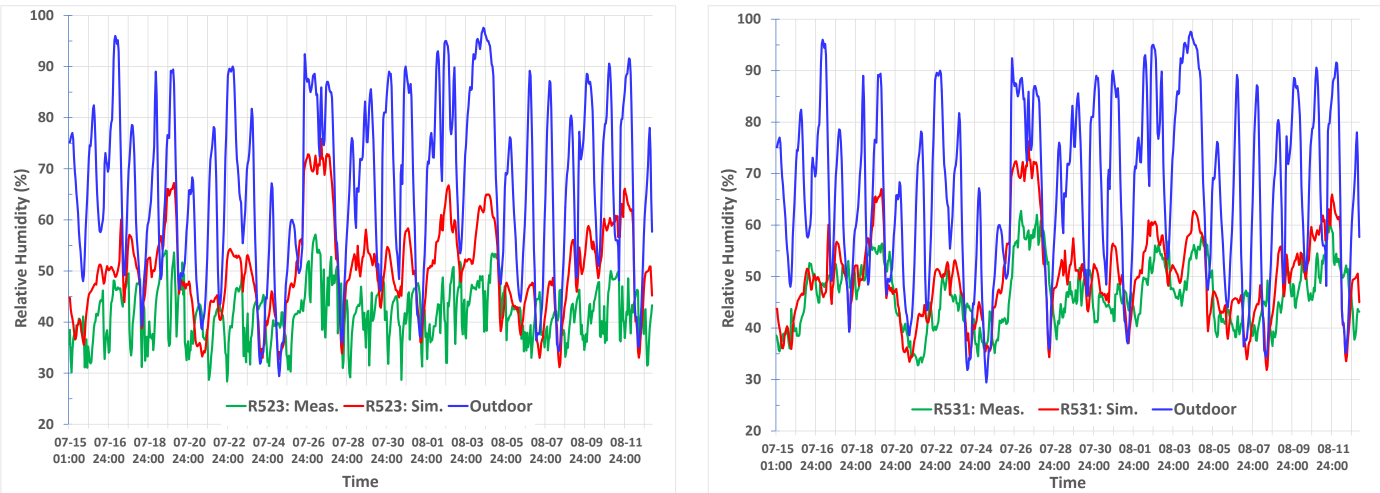

Figure 6. *Cont.*

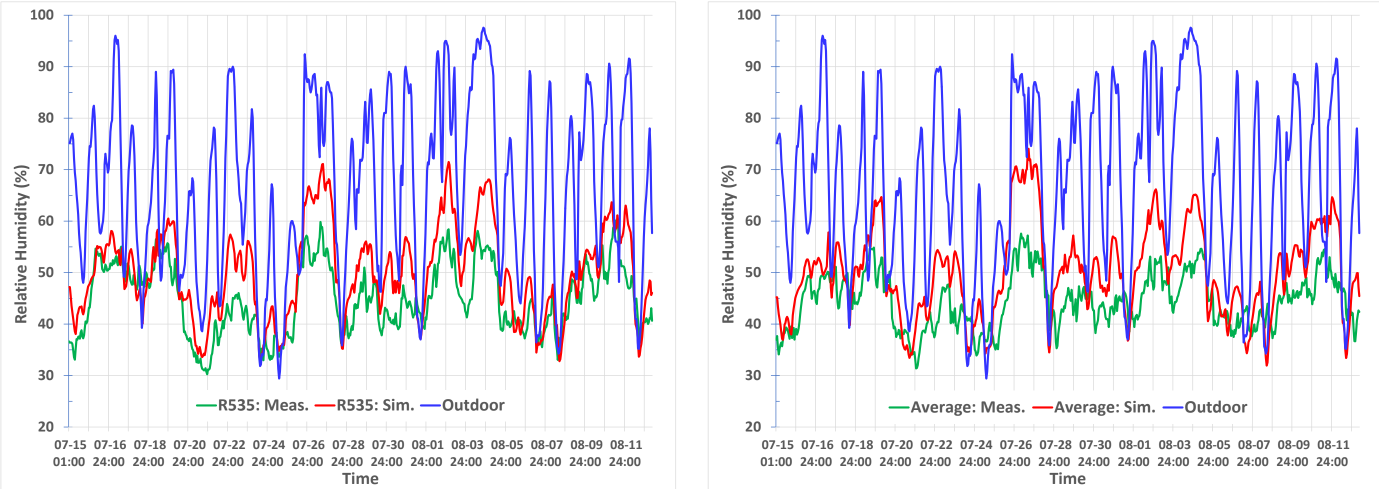

Figure 6. Comparison of indoor relative humidity of bedrooms (R523, R531, and R535) and their average value.

Table 3. RMSE and MBE of temperature and relative humidity for bedrooms (523, 531, and 535) and their average value.

Error	R521	R531	R535	Room Average
RMSE-T (°C)	1.7	0.9	1.0	1.0
RMSE-RH (%)	12	7	7	8
MBE-T (%)	−3	2	−2	−1
MBE-RH (%)	20	7	12	13

2.3.2. Energy Use Intensity Data

The second calibration method includes comparing the annual energy use intensity data of the building models with old (no retrofit) and new constructions with published data of large groups of similar real buildings. To this end, the following assumptions were used:

1. The service hot water (SHW) energy load was not accounted for in the model prediction but was calculated based on the typical SHW loads of NECB 2017 (500 W/person for bedrooms). Based on the NECB 2017 SHW loads and usage schedule, the calculated annual energy use of SHW was 218,804 kWh;
2. The seasonal boiler efficiency for SHW was fixed at 60% for old construction and 75% for new construction [45];
3. Natural gas was used for space heating. The electrical energy used for heating in the simulation model was therefore converted to gas furnace heating, assuming a furnace efficiency of 80% for old construction and 90% for new construction;
4. For the annual cooling energy use of the building, the COP coefficient was fixed at 2.5 for old construction and 3 for new and retrofit construction;
5. The energy use for the kitchen (cooking), exterior lighting, hair salons, exercise rooms, etc., of real buildings, were not accounted for in the model predicted EUI. These diverse energy uses may constitute a significant portion of the total building energy use. The predicted EUI is therefore expected to be significantly lower than that of real similar buildings.

Since there are many configurations of wall and roof insulation of old buildings in the 1980s, the building model for old construction was run for three types of wall and roof insulation: (1) typical 1980 construction with no wall insulation (U-factor for walls = 1.415 W/m^{2}K; U-factor for roofs = 0.445 W/m^{2}K); (2) typical 1980 construction with 1.5″ wall insulation (U-factor for walls = 0.557 W/m^{2}K; U-factor for roofs = 0.445 W/m^{2}K); (3) typical 1980 construction with 1.5″ wall insulation and retrofitted roofs.

Simulations are carried out for five Canadian cities (Montreal, Ottawa, Toronto, Calgary, and Vancouver) to obtain a national average value of EUI. The total building heated area, not including the basement, was 4208 m^2. Table 4 compares the simulated total EUI (for heating, cooling, lighting, and SHW) with published benchmark data on LTCH across Canada. As expected, the predicted EUI was lower by a minimum of 12% for old buildings and 27% for new buildings than the published data of real buildings due, among other factors, to the aforementioned model assumptions, particularly the uncounted energy use of the food preparation services in the building. Industrial kitchens account for a substantial energy use commensurate with building occupancy (number of meals). For example, the national average EUI of a typical restaurant is 3.17 GJ/m^2 [46].

Table 4. Calibration of the model EUI with published benchmark data of LTCH.

Construction	H + C + L (kWh/m^2)	Total (kWh/m^2)	EUI (GJ/m^2)	Benchmark EUI (GJ/m^2)
New	80	149	0.54	0.74 (>2010) [47]
Old	160	247	0.89	1.3 [47]; 1.04 [48]; 1.01 to 1.95 [49]

2.4. Procedure to Evaluate Overheating Risk

Overheating is different from thermal discomfort, although they are related. Thermal discomfort indicates an instant perception (feeling) of environmental conditions. However, overheating on the objective dimension indicates the cumulative effect of heat on thermal comfort, heat stress, health, and wellbeing of building occupants directly exposed to such overheating events. On the subjective dimension, overheating indicates the occupant dissatisfaction with the overall (long-term) thermal comfort level, health, and wellbeing under direct exposure to overheating events. So far, there exists no unique standard or agreed-upon procedure to evaluate overheating risk in buildings. However, the common steps in any procedure are summarized in Figure 7 below. The first step is to set the time domain to evaluate overheating risk. The time domain can be the period of the indoor overheating event (which may be longer than the outdoor heat waves), a fixed summer period, the entire cooling season, or an entire year. The second step is to evaluate overheating risk for fixed building spaces or for building occupants. The fixed-space approach is to isolate a building space occupied for a certain period of time and perform overheating risk analysis irrespective of other building spaces, which may be as well occupied by the same occupants during other daytime periods. In this case, the cumulative day-to-day effect of heat on building occupants was not carried over the evaluation time period. An example of this approach is to evaluate overheating risk in living rooms (occupied during daytime) irrespective of bedrooms (occupied during nighttime for sleep) in residential buildings or to evaluate overheating risk in dedicated cool rooms irrespective of other building spaces in institutional or residential buildings. However, the occupant-based approach accounts for the dynamic personal exposure conditions by tracking occupant movement in the entire building and evaluating the overheating risk in all occupied spaces during a complete (24 h) day exposure. In this case, the cumulative day-to-day effect of heat on occupants (e.g., cumulative water loss or effect of sleep deprivation on the thermal response of occupants to heat during daytime) was carried over the evaluation time period. The third step as to evaluate overheating risk from the perspective of either thermal comfort or heat-related health effects. Examples of the comfort perspective include indicators such as unmet hours, degree hours or degree days, or thermal autonomy. An example of the health perspective is to account for the cumulative effect of heat on body dehydration due to sweating and inadequate water replacement (rehydration), maximum core temperature, or heart rate or blood pressure to avoid any health injury. This study adopted the occupant-based approach and heat-related health effects to analyze overheating risk in buildings.

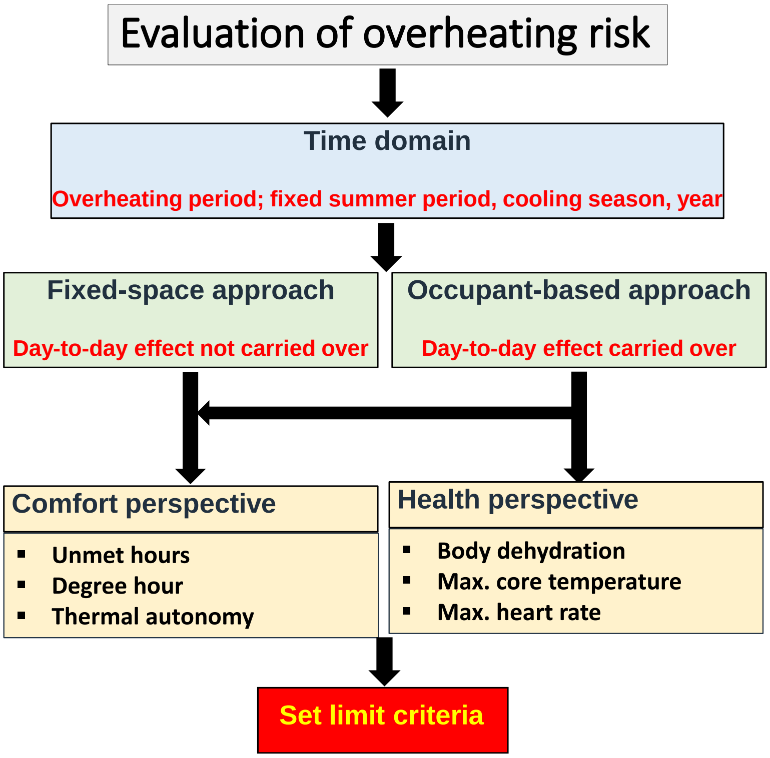

Figure 7. General procedure for overheating risk evaluation.

2.4.1. Identification of Overheating Events

The adopted approach for overheating risk analysis used the transient standard effective temperature (SET) as an index for heat stress [50]. SET was used to identify outdoor heat waves and indoor overheating events that result in heat stress or thermal discomfort to people directly exposed to such heat events. Overheating events were characterized by three attributes: duration (denoted by DUR, days), severity (or magnitude denoted by SETH, °C·h), and intensity (denoted by INT, °C).

The duration of indoor overheating events is the number of consecutive days (N) on which the daily magnitude of a heat event ($SETH_{d,i}$; Equation (4) below) exceeds a fixed minimum value:

$$\text{DUR} = \text{N};\ \text{with}\ \text{SETH}_{\text{d,i}} > \ \text{SETH}_{\text{min}}\ \text{for each day}\ (\text{i} = 1, \text{N}) \tag{1}$$

The duration attribute indicates the total exposure time of the overheating event. Indoor overheating events are separated from each other if there is at least one recovery day between them for which the daily magnitude ($SETH_{d,i}$) is lower than or equal to its minimum value ($SETH_{d,i} \leq SETH_{min}$).

The severity (or magnitude) attribute of an overheating event indicates the cumulative heat stress levels times the exposure time over the duration (N) of the overheating event. The severity attribute (SETH) is expressed as follows:

$$\text{SETH} = \sum_{i=1}^{N} (\text{SETH}_{\text{n,i}} + \text{SETH}_{\text{d,i}}) \tag{2}$$

With:

$$\text{SETH}_{\text{n,i}} = \sum_{\text{t\_sleep}}^{\text{t\_wake}} (\text{SET}_{\tau} - \text{SET}_{\text{n}})^{+} \cdot \Delta\tau \tag{3}$$

$$\text{SETH}_{\text{d,i}} = \sum_{\text{t\_wake}}^{\text{t\_sleep}} (\text{SET}_{\tau} - \text{SET}_{\text{d}})^{+} \cdot \Delta\tau > \text{SETH}_{\text{min}} \tag{4}$$

where:

i: Day index of the overheating event period;

t_sleep: Starting time for sleep (h);

t_wake: Ending time for sleep (h);

SET_τ: Sub (or)-hourly value of SET of the space being occupied at time (τ) during day or nighttime (°C);

SET_n: Threshold value of SET for a sleeping occupant during nighttime (°C);

SET_d: Threshold value of SET for an active (wakeful) occupant during daytime (°C);

$SETH_{d,i}$: Magnitude of a heat event occurring over a daytime period of day (i) (°C·h);

$SETH_{n,i}$: Magnitude of a heat event occurring over the preceding nighttime period of day (i) (°C·h);

$\Delta\tau$: Time step resolution (h).

The symbol (+) in Equations (3) and (4) indicates that only positive values were considered. The start and end times of sleep (t_sleep; t_wake) were fixed to 10:00 p.m. and 7:00 a.m., respectively.

A daily indoor heat event was counted only if its daytime magnitude ($SETH_{d,i}$) exceeds the minimum value set to $SETH_{min}$ = 4 °C·h to limit body dehydration lower than 1%. Similarly, the preceding nighttime magnitude ($SETH_{n,i}$) was counted in Equation (2) only if the daytime magnitude ($SETH_{d,i}$) exceeded the minimum value.

The intensity of an overheating event was the ratio of severity to (24* N). The intensity indicates the average deviation of SET over its threshold values throughout the overheating event.

Equation (2) was evaluated for building spaces for which at least two spaces were occupied during a 24 h period, one for daytime and one for nighttime or sleeping. For buildings where sleeping environments are not offered (such as offices and schools), Equation (3) was not used in Equation (2).

It should be noted that the sub-hourly values of SETτ were calculated for a reference young (average age) adult, but the threshold values (SET_d and SET_n) were values equivalent to those for older people (more details are found in [51]).

The evaluation of Equations (1)–(4) will need known threshold values of SET for daytime (SET_d) and nighttime (SET_n) exposure and reference persons undergoing the exposure to indoor heat events. The threshold values of SET should be chosen to maintain acceptable limits of thermal comfort without any adverse heat-related health effects. These thresholds are therefore dependent on the type of buildings (residential, schools, offices, etc.) and occupants (children under 15 year old, young adults, older people with or without pre-existing health conditions, etc.) and whether or not occupants are acclimatized to heat under the local climate and/or given opportunities to adapt to heat in the built environment. Furthermore, the reference person (in terms of the performed activity level and worn clothing insulation value) varies with the built environment being occupied during the heat events. In this study, the SET threshold values were calculated based on a new comfort index (called metabolic-based predicted mean vote, MPMV) for young and older adults in wakeful or sleep state [40]. For long-term care buildings where occupants are offered no means to self-adapt to heat but receive continuous assistance in their daily lives, the threshold of SET_d is determined to maintain neutral comfort conditions for older people with MPMV = 0. For sleep comfort, the threshold value of SET_n was calculated at MPMV = 0.25, with a corresponding value of SET_n = 32 °C. Table 5 lists the suggested (calculated) threshold values of SET for LTCHs. The daytime threshold value SET_d for unacclimatized older occupants was close to the USGBC heat index threshold value of 27 °C (corresponds to SET = 26.8 °C at a relative humidity of 50% and clothing insulation of 0.6 clo.) for hospitals and nursing homes [52]. Public Health England [29] and BC Housing [53] specify a lower threshold temperature of 26 °C. Recent field studies in homes with older occupants in South Australia (hot climate) found that self-reported perceptions of health and wellbeing correlated with thermal comfort perception, and good health and wellbeing were reported for indoor temperatures below 28 °C [54], which is close to the acclimatized value of SET_d = 28 °C (at RH = 50% and 0.6 clo).

Table 5. Suggested threshold values of SET_d and SETn for LTCH.

Reference Young Person [+]	SET_d (°C) [++]	SET_n (°C)
Wake: 1 met and 0.5 clo Sleep: 0.7 met and 1.64 clo	26.8 (May) 28 (June to September)	32

[+] Older persons are assumed to have a 20% lower metabolic rate than young adults; [++] occupants are assumed acclimatized to heat in summer, except in May.

2.4.2. Procedure to Develop Overheating Limit Criteria

Built environments may be subject to various types of overheating events with different durations, intensities, and severities during hot weather conditions. Furthermore, internal casual heat gains of buildings from lighting, equipment, and occupant activities may exacerbate overheating events. The latter may, therefore, start before and end after outdoor heat wave events, and may even become significant with mild outdoor heat waves. To avoid any heat-related health problems for building occupants and to declare a building is safe for occupancy, these overheating events have to be subject to some limit criteria. The limit criteria depend on the approach used to evaluate the overheating risk from either the comfort or health perspective. The limit criteria are therefore applied to the key performance indicators or metrics used to evaluate the overheating risk. The adopted approach in this study used heat-related health indicators, namely, the cumulative body water loss (dehydration) due to the fact of sweating and inadequate water replacement and the maximum body core temperature during the exposure period of overheating events.

Body dehydration was the first cause of mortality followed by heatstroke (core temperature higher than 40 °C) during the 2003 European heat wave [55]. Dehydration is also one of the most frequent causes of hospitalization in older people [56,57]. Studies in LTCHs revealed that 20% to 31% of older residents were dehydrated [58,59]. The ISO:7933-2004 standard [60] sets the maximum body dehydration rate to 3% of body weight for healthy young adult workers under up to eight hours of sustained hot exposure conditions and indicates that higher dehydration rates are accompanied by increased heart rates and reduced sweating sensitivity. Other studies [61] found that a dehydration level of 2% in adults may result in a significant deterioration in cognitive functions (short-term memory, arithmetic ability, and visuomotor tracking). For older occupants in built environments where heat exposure can be many days long, the maximum dehydration rate should be lower than ISO:7933 due to the fact of their age-related physiological changes (e.g., kidney function, thirst perception, and lower body water content [62]). For example, older people are less sensitive to thirst and heat, and those people who are sick have limited mobility to rehydrate themselves. Cardiovascular and renal diseases and medications can exacerbate the situation [63]. Dehydration rates as low as 2% for older people can have significant health issues, such as lower endurance and increased risk of heat exhaustion and fatigue, and impaired cognitive functions and performance responses [58,64]. If people can freely rehydrate themselves (by regularly drinking beverages to replace body water loss), the maximum dehydration rate can be relaxed to a higher value. Community surveys undertaken in Canada [65] showed that average-age adults (31 to 50 years) and older people (above 51 years), respectively, drank 2.031 and 1.791 L/day of beverages. This corresponds to hydration rates of 79% for average-age adults and 70% for older people based on the Canadian recommended fluid intake of 2.550 liter/day for sedentary people. Similar studies in Europe revealed that a hydration rate of 81% is common in the adult population [64].

The second heat-related health effect is to limit the body's core temperature to avoid any health problems. International standards for heat exposure in workplaces limit the core temperature to a maximum value of 38 °C for healthy average-age adults under sustained hot exposure conditions of up to eight hours [66,67]. This temperature limit may not, however, be suitable for sustained hot exposure conditions during long overheating events lasting many days. Furthermore, for frail people with chronic diseases, this maximum value can be very dangerous to their health. For example, studies in intensive care units found that when indoor temperatures exceeded 30 °C, the critically ill (but without fever) patients (average age of 49 years) started to experience hyperthermia with an average core temperature higher than 37.7 °C [68]. Therefore, a lower threshold limit for the core temperature should be used. The proposed limit value to accommodate all types of healthy people is set to the upper limit of the normal range at rest, which is 37.6 °C [69].

In light of the aforementioned studies, Table 6 summarizes the suggested limits for body dehydration rate and maximum core temperature of older residents in LTCHs for overheating risk analysis.

Table 6. Suggested thresholds of body dehydration and rehydration rates and maximum core temperature for LTCHs.

Rehydration Rate (%)	Dehydration Rate (without Rehydration) (%)	Dehydration Rate (with Rehydration) (%)	Maximum Core Temperature (°C)
80	2	10	37.6

The limit criteria to declare a space or building to be overheated or not is to limit the attributes of the various types of overheating events. Overheating is declared if at least one of the following three criteria is satisfied:

$$\mathrm{DUR} \geq \mathrm{DURL};\ \mathrm{INT} \geq \mathrm{INTL};\ \mathrm{SETH} \geq \mathrm{SETHL} \tag{5}$$

where DURL, INTL, and SETHL are the limit values of duration, intensity, and severity of overheating events, respectively. These limit criteria are related to heat-related health indicators. It is found that the duration and severity attributes correlate well with the cumulative body dehydration (water loss) and the intensity attribute correlates well with the maximum body core temperature [50,51]. Body dehydration and core temperature should be calculated using suitable physiological models of the human body. In this work, the two-node bioheat models of Ji et al. [70,71] for average young and older adults were used.

The above limit criteria (Equation (5)) depend on building type, occupant's vulnerability to heat, and local climate. The limit criteria can be determined by building simulations using representative building models with new and old constructions. To bracket the upper and lower bounds of overheating risk in such buildings, simulations were to be carried out for buildings with various passive mitigation strategies and extreme climate data in selected localities. Building simulation generated the required inputs of the indoor conditions (air temperature and humidity, mean radiant temperature, and average air speed around occupants) together with the reference occupant inputs (Table 5) to execute the physiological models of the human body to calculate the sub (or) hourly values of SET and body dehydration and core temperature. The overheating events were then identified using Equations (1)–(4), and their attributes were plotted against the heat-related health indicators. A regression analysis was then used to develop the corresponding limit criteria based on the personal data in Table 6.

3. Results

3.1. Overheating Limit Criteria

Following the procedure of Section 2.4, the calibrated models of LTCHs with new and old constructions were set-up to cover four measures to bracket the bounds of overheating risk. These measures included reference (typical) cases (closed windows with internal typical blinds), exterior roller shadings, fixed exterior overhangs, and natural ventilation by opening operable windows and internal doors. The simulations were carried out in five key Canadian cities (Montreal, Ottawa, Toronto, Calgary, and Vancouver) using two extreme climate data files selected from the historical period (1986 to 2016) and future (simulated) midcentury climate projection with global warming of 2 °C (2034 to 2064). The selection of the extreme weather years was according to the method of Laouadi et al. [72]. Table 7 lists the selected years.

Table 7. Selected extreme weather years for simulation for each city.

Period	Montreal	Ottawa	Toronto	Calgary	Vancouver
Historical	2010	2010	2006	2007	1989
Future	2047	2054	2060	2052	2052

The simulation results were post-processed to identify overheating events using the occupant-based approach as outlined in Section 2.4. To this end, the spaces occupied by residents over 24 h should be identified a priori. In LTCHs, residents were assumed to dwell in the lounge room during the periods of morning breakfast, lunch, and dinner, and in their bedrooms during the reminder periods of daytime and nighttime for sleep. Table 8 shows the space occupancy pattern over a 24 h period.

Table 8. Time periods of spaces occupied by the same resident over a 24 h period in LTCHs.

Time (h)	1–7	7–8	8–9	9–12	12–13	13–17	17–19	19–22	22–24
Space	bedroom	bedroom	lounge	bedroom	lounge	bedroom	lounge	bedroom	bedroom
Activity	sleep	daytime	breakfast	daytime	lunch	daytime	dinner	daytime	sleep

Figures 8–10 show the plots of the attributes of the overheating events (duration, intensity, and severity) versus the cumulative body water loss and maximum body core temperature. Based on the input data of Table 6, the limit criteria for duration (DURL), intensity (INTL), and severity (SETHL) are given below:

$$\mathrm{DURL} = 4 \text{ days};\ \mathrm{INTL} = 5\ ^\circ\mathrm{C};\ \mathrm{SETHL} = 87\ ^\circ\mathrm{C{\cdot}h} \tag{6}$$

It should be noted that the duration limit of the overheating events in Equation (6) may be different than the duration of outdoor heat waves. Indoor overheating events may start before and end after outdoor heat waves. In this regard, short heat waves with a duration of a few days may result in longer overheating events. Similarly, mild heat waves may result in severe overheating events, depending on the internal heat gains of spaces and solar radiation. Therefore, during heat waves, the days before and after them should be included in the calculation of DURL using Equation (1) to determine at what day after the heat wave the duration limit (DURL) is reached and the space is considered overheated.

It is often desirable and practical to translate the intensity limit (INTL) to the absolute air temperature limit in the space during the daytime. INTL indicates the average deviation of SET from its day and nighttime threshold values for the entire period of the overheating event. However, INTL can be bracketed between overheating events with cool nights and events for which the deviation of SET for the entire event period is constant and uniform. This is translated into the following equation:

$$\mathrm{INTL}\ (\text{uniform deviation}) \leq \mathrm{SET_{max}} - \mathrm{SET_d} \leq \frac{24}{15}\cdot\mathrm{INTL}\ (\text{cool nights}) \tag{7}$$

where $\mathrm{SET_{max}}$ is the maximum daytime value of SET (corresponding to a body core temperature close to the limit value of 37.6 ± 0.12 °C, Figure 10), and the factor 15/24 indicates the proportion of the daytime hours (15 h) over a 24 h period.

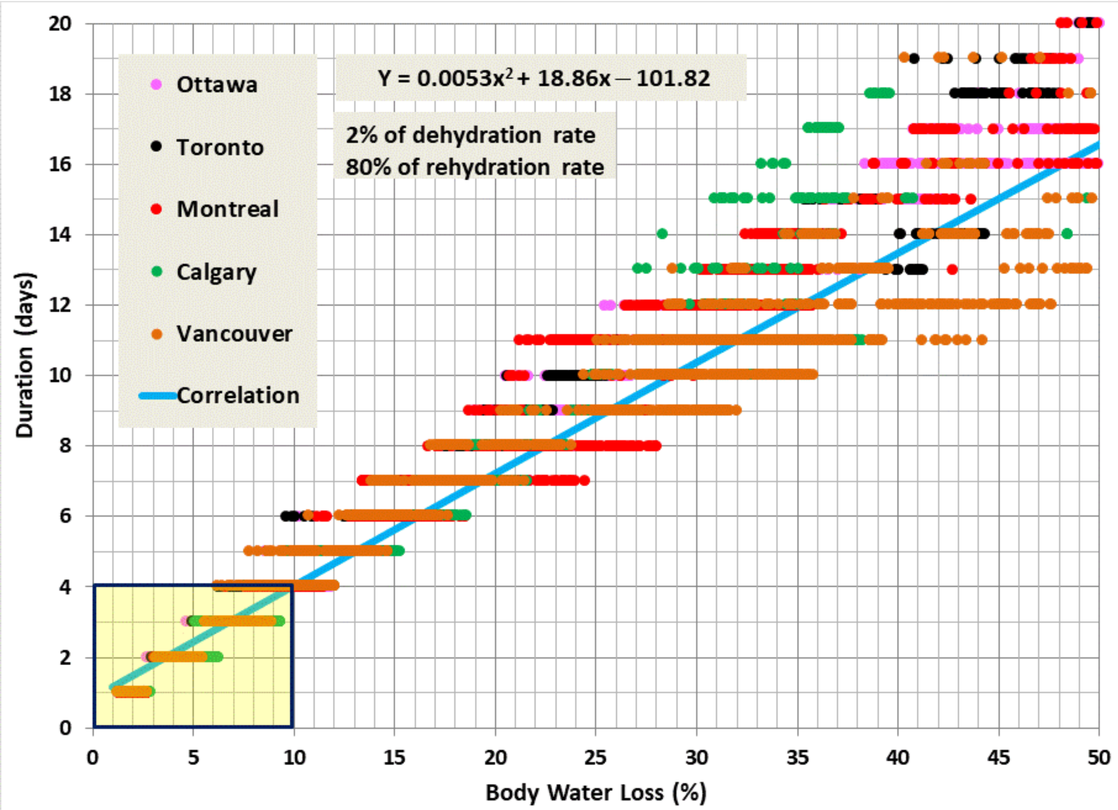

Figure 8. Duration of overheating events versus body water loss in LTCHs.

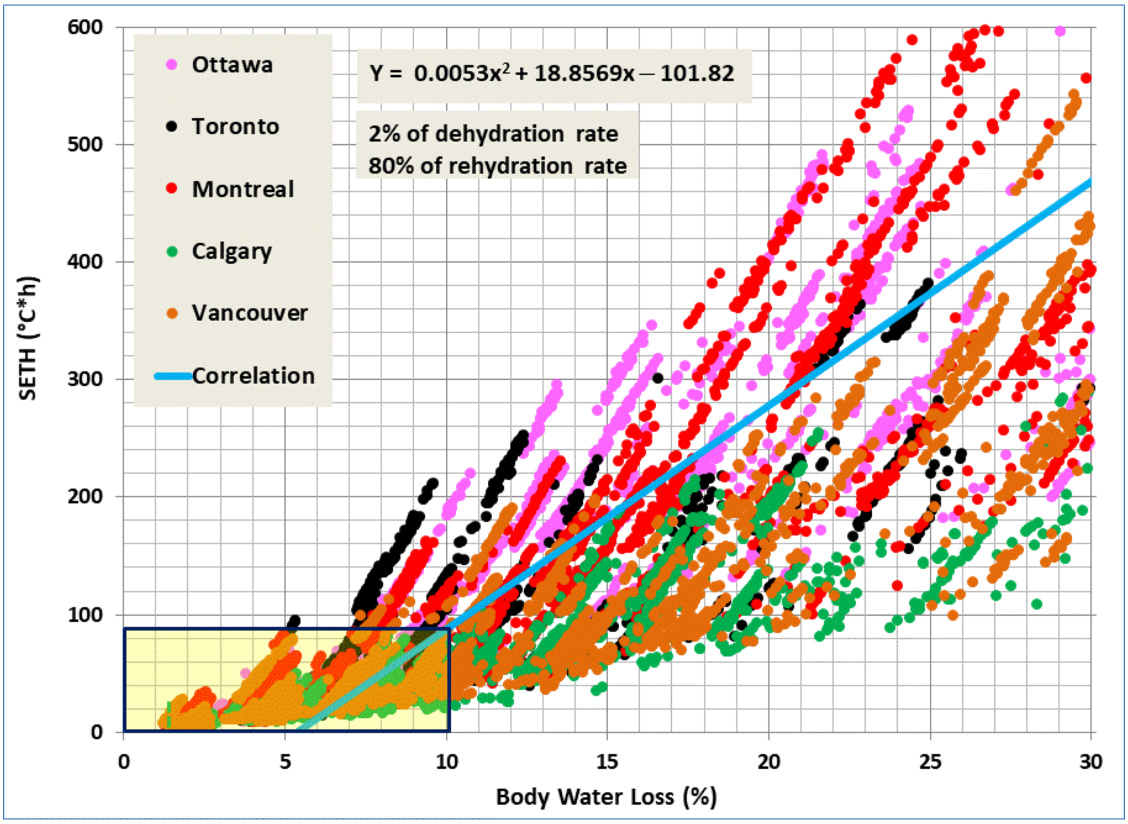

Figure 9. Severity of overheating events versus body water loss in LTCHs.

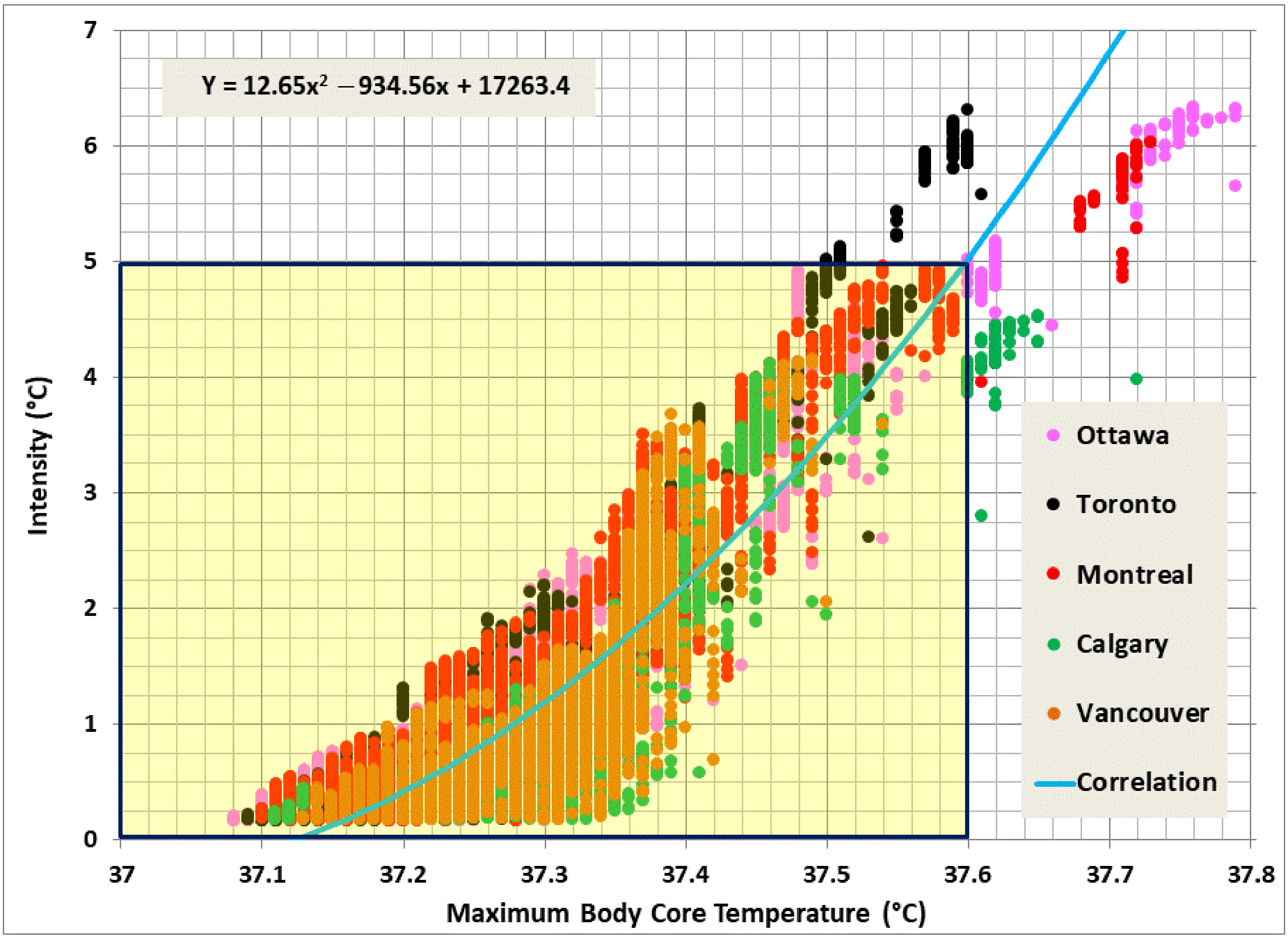

Figure 10. Intensity of overheating events versus maximum body core temperature in LTCHs.

By accounting for Equation (6) and the daytime threshold value of SET of Table 5, Equation (7) may thus be reduced to:

$$33\ ^\circ\mathrm{C} \leq \mathrm{SET}_{max} \leq 36\ ^\circ\mathrm{C} \quad (8)$$

Equation (8) indicates that SET_{max} in the LTCHs ranged from 33 °C for the overheating events resulting in warm nights for which sleep quality was affected and 36 °C for events with hot daytimes but cool nights for which sleep quality was not affected. The median value of SET_{max} for intermediate situations with random hot days and warm nights was 34.5 °C, which may be used as an alternative overheating criterion to INTL = 5 °C. It should be noted that studies in intensive care units during summer heat waves found that bedbound critically ill (but without fever) patients (average age of 49 years) started to experience hyperthermia at indoor temperatures higher than 30 °C [68]. This situation corresponds to SET = 33.7 °C (assuming relative humidity = 50%, clothing insulation including bed and mattress = 1.64 clo; and metabolic rate = 0.8 met), which is within the limits of Equation (8).

3.2. Inter-Comparison of Overheating Criteria

The proposed overheating method was compared with selected existing methods. Currently available methods are based on the fixed-space approach and use thermal comfort indicators and ad hoc limit criteria. Methods applicable to LTCHs include CIBSE TM52 [28], Passive House Institute (PHI) [73], and BC Housing [53]. The CIBSE

TM52 uses the adaptive comfort for sensitive people (building category I) to calculate three criteria: (1) hours of exceedance (HE) not to exceed 3% of the summer (May to September) space occupancy hours; (2) daily weighted degree hour (WDH) in any day not to exceed 6 °C·h; and (3) maximum operative temperature not to exceed 4 K above the adaptive threshold value. Overheating is declared if any two out of three criteria are satisfied. The PHI criterion uses a fixed temperature threshold of 25 °C, and the hours of exceedance do not exceed 10% of the annual occupancy hours. BC Housing method uses the ASHRAE-55:2020 [74] adaptive thermal comfort and limits the HE to 20 h in the summer period. Another variant criterion is the cumulative degree hours (DH) as used in other research studies but without defined limit criteria (e.g., [75,76]). DH is calculated in a similar way as the WDH with fixed or adaptive temperature threshold values but covering the entire summer (or year) period. DH can be regarded as a weighted HE (weighted by temperature difference).

The above overheating criteria were applied to the bedroom spaces. The TM52 criteria were applied when residents were not sleeping from 7:00 a.m. to 10:00 p.m. (sleep was assessed using a different criterion in TM59). However, PHI and BC Housing criteria were applied to the full (24 h) day occupancy. The proposed method uses the occupancy schedule as listed in Table 8, thus covering the spaces and time periods when residents are in bedrooms and common spaces.

For the comparison study, the developed LTCH models with new and partially retrofitted old constructions were simulated for the four mitigation measures of overheating: (1) reference case (Ref) with typical interior blinds, which remain closed with windows during the entire summer period, but interior doors of bedrooms and offices are assumed 50% open due to the occupant movement to/from the common spaces; (2) reference case, but the internal blinds are replaced by external roller screens (ES) with an openness factor of 5%; (3) reference case, but natural ventilation (VO) is applied by opening windows and internal doors of bedrooms and offices if their occupants start to feel thermal discomfort and the indoor temperature exceeds the outdoor temperature; and (4) reference case, but the common spaces (lounges for old buildings; lounges and corridors for new buildings) are mechanically cooled (CONC) and maintained at 24 °C during the summer period.

The city of Vancouver (latitude = 49.28°; longitude = 123.12° W) was selected to carry out simulations. Vancouver has a coastal climate with mild and rainy winters and cool and sunny summers [11]. The extreme year of 1989 with a warm and humid heat wave in June 24 (temperature ranges from 19.85 to 28.96 °C, and relative humidity from 61% to 97%) was selected from the historical climate datasets of 1986 to 2016 (collected from available observation data) using the methodology of Laouadi et al. [72]. This year is, however, not considered as extreme based on the city heat warning system to declare heat waves when there are two or more consecutive days of daytime maximum temperatures equal to 29 °C or higher and nighttime minimum temperatures equal to 16 °C or higher (relative humidity not accounted for) [6].

Figure 11 shows the relationship between the indices of SETH and TM52-HE for all bedrooms of old and new buildings (note some data are not shown to fit the axis ranges). The results for the SETH index indicate that most bedrooms are not overheated. By contrast, TM52-HE indicates that most bedrooms are significantly overheated. Furthermore, there is a very weak relationship between SETH and HE, being dependent on building construction, space operation, and local climate (not shown in the figure). The relationship is worse, particularly when occupants dwell in multiple and different spaces during the daytime, such as option CONC. It is therefore difficult to set a single health-based limit criterion equivalent to the comfort-based criterion (HE or similar indicator) that is applicable to any climate and building.

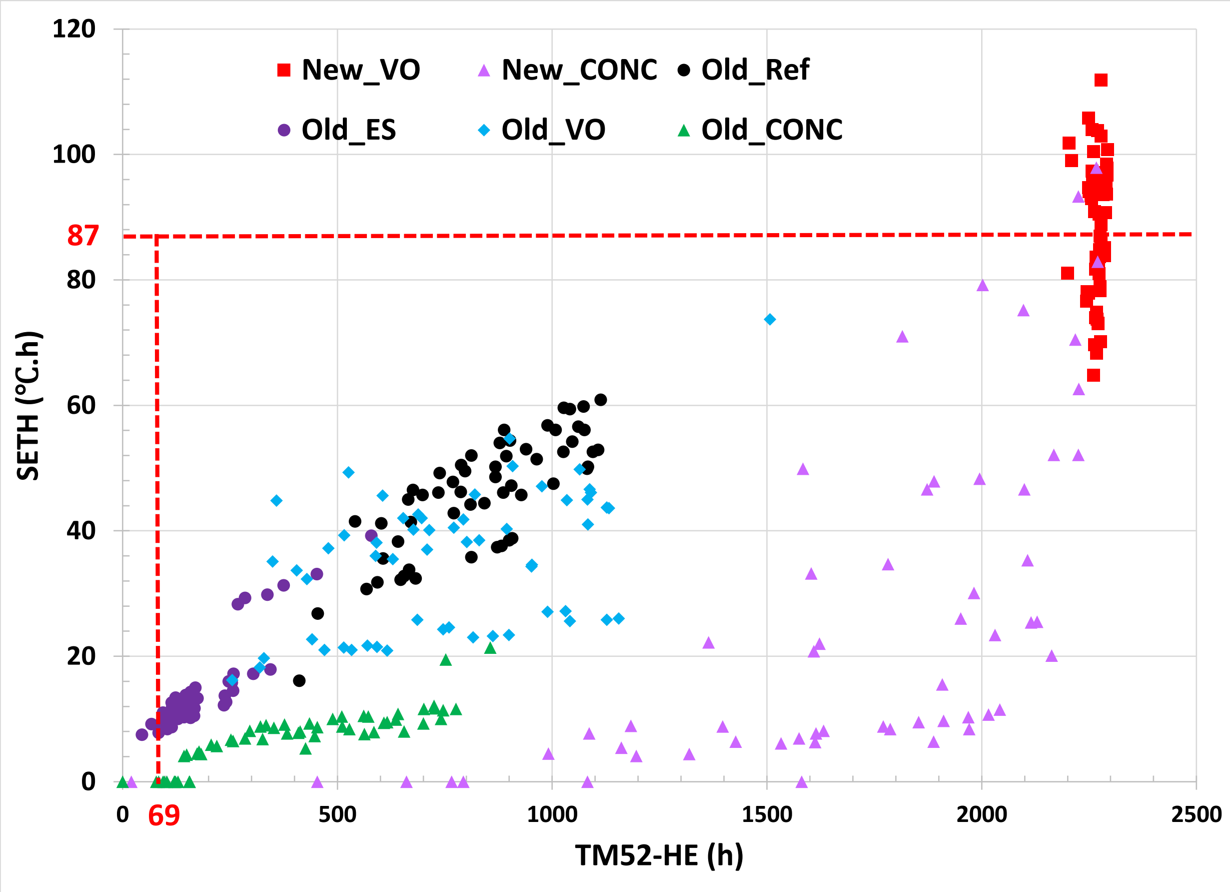

Figure 11. Relationship between SETH and TM52-HE for all bedrooms of old and new LTCHs (note both SETH and HE limit values are shown in the red color; some data points are truncated to fit the axis ranges).

For further result scrutinization, Table 9 compares the overheating criteria for bedroom #523 of old and new buildings (note the INT indicator is lower than its limit value and, therefore, not included in the table). According to the proposed method, old buildings are not considered overheated under such a mild maritime climate. For new buildings, the proposed method indicates that the DUR or SETH indicators predict the building is overheated, except for the strategy to cool the common spaces (CONC). However, the TM52, PHI, and BC methods predict that both old and new buildings are overheated.

A common background (benchmark) to explain such results is to investigate occupant dissatisfaction regarding the overall thermal comfort level (and heat-related health symptoms if available) during the periods of overheating events. To this end, the indoor temperature in the bedroom and comfort level, as would be perceived by residents during an overheating event (3–7 June), are plotted in Figures 12 and 13 for old and new buildings, respectively. Thermal comfort for older people (having an average metabolic rate of 20% lower than young adults) in a wakeful or sleeping state was calculated using the MPMV model [40]. For old buildings, the bedroom temperature varies between 25 and 30.5 °C. Under such bedroom conditions and those for the common spaces, the comfort level of residents is within the comfort range of slightly warm (MPMV = 1) and slightly cool (MPMV = −1). It was therefore expected that residents would be satisfied with their exposure conditions, and no significant overheating issue would be perceived overall. These findings are similar to the field study of [25] in LTCH for which the bedroom temperatures were between 24.8 and 27.7 °C, except for some days with higher temperatures. Their field study found a disparity between the overheating criteria of TM52 and TM59 and field surveys. The survey data found that the majority of residents perceived their environmental conditions as thermally neutral even when indoor temperatures were over 30 °C. Furthermore, none of the residents expressed any concern about their health being affected by excessive heat.

The situation for new buildings was, however, different than old buildings. The proposed method predicts that all measures result in space overheating, except the one to cool the common spaces (CONC). All other overheating criteria predicted excessive overheating in bedrooms. The comfort results of Figure 13 indicate, indeed, that the CONC strategy results in overall thermal comfort within the comfort range (MPMV within ±1), followed by the natural ventilation strategy with limited occurrences of thermal discomfort at MPMV > 1.

In view of these results, one can ascertain that the overheating analysis using the proposed method is consistent with the overall thermal comfort level during the periods of overheating events. This is in contrast to the other selected methods. TM52-HE is stringent and may be relaxed to a higher limit value to be consistent with the occupant satisfaction survey data. This holds as well for the PHI criterion. BC Housing criterion seems, however, not achievable in practice using passive measures.

Table 9. Inter-comparison of overheating criteria for bedroom #523 of old and new LTCHs.

Criterion	Proposed (Old/New)						TM52				BC		PHI	
Measure	**DUR (d)**		**SETH (°C·h)**		**HE (%)**		**WDH (°C·h)**		**ΔT_{max} (°C)**		**HE (h)**		**HE (%)**	
Ref	2	76	33	4196	29	98	43	124	4.2	9.2	1558	3672	29	42
ES	1	14	9	371	4	100	18	86	2.1	6.3	534	3583	20	41
VO	1	6	21	69	23	99	32	59	3.7	5.5	1393	3672	28	42
CONC	1	1	7	11	12	88	28	51	3.4	4.2	823	3394	24	41

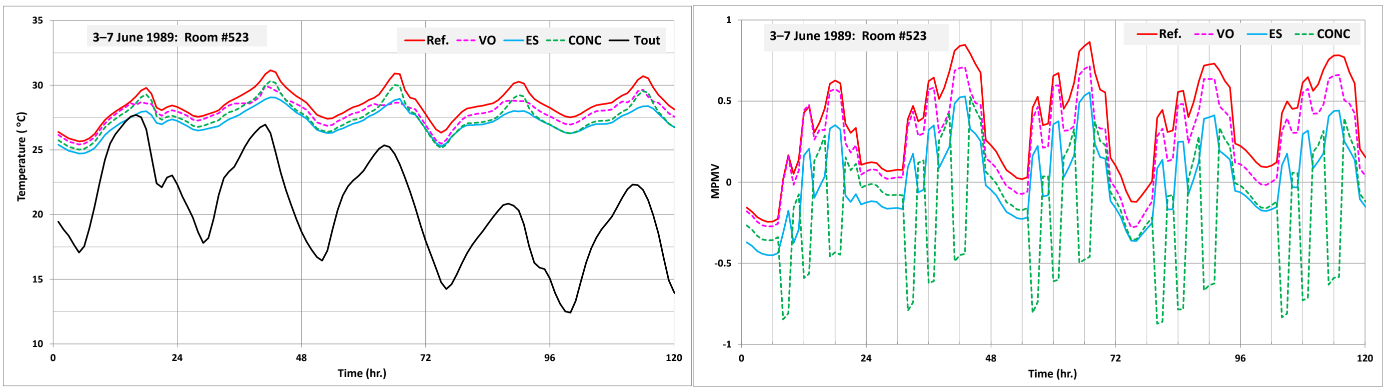

Figure 12. Bedroom temperature and thermal comfort of residents in old LTCH.

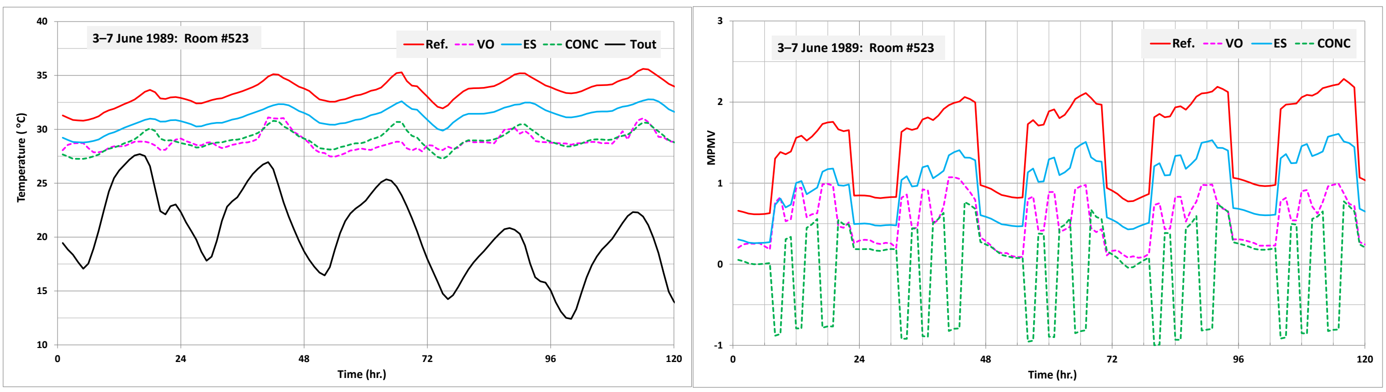

Figure 13. Bedroom temperature and thermal comfort of residents in new LTCHs.

4. Discussion

This study shows how building simulation can be combined with bioheat models of the human body to analyze overheating risk in buildings and develop limit criteria from the heat-related health perspective. Building energy simulation has become a standard practice in high energy efficiency designs of buildings. However, for overheating risk analysis, a building simulation will have to fulfill certain specific requirements to properly account for the interaction of occupants with the indoor space and operation of building services. One of the main requirements is the simulation software has to have capabilities to model heat and air flows in building interior spaces and produce time series results of indoor conditions close (within an order of magnitude) to real settings. In this study, general simulations models of LTCHs were built from a real monitored building (geometry and orientation), but inputs of construction data, internal heat gains, and air leakage data are taken as average values of a set of similar buildings or typical values from applicable building energy code for a given locality and construction year. The results of this approach revealed two important findings. First, the developed building model of LTCHs results in indoor conditions very similar to the field measurement data during the monitoring period. Second, the simulation software (EngeryPlus) can predict moisture mass transfer in terms of indoor humidity levels (which is not required for energy simulation) with sufficient accuracy in naturally ventilated buildings if an airflow network is combined with thermal simulation. Both temperature and relative humidity were very important to evaluate thermal comfort and overheating risk. The proposed calibration approach may thus represent a basis for simulators to develop simulation models of various types of buildings for overheating risk analysis.

The proposed (health-based) general approach to analyze overheating risk and develop limit criteria is something new in this field of research in that it accounts for the personal exposure conditions of building occupants. Personal exposure conditions may change on a daily basis with time as occupants may move from one space to another to adapt to heat or conduct different activity levels, including sleep, and therefore the cumulative effect of heat on the thermal comfort and health of occupants can be quantified during the periods of overheating events. This study considered two well-known heat-related health indicators directly related to mortality, namely body core temperature and dehydration (water loss) of occupants in good health conditions. Core temperature is an indicator for many heat-related health symptoms, including heat cramps, heat syncope, heat exhaustion, fatal heat stroke, etc. [77], and may reach its safe limit value (for example, 38 °C for workers in hot environments [67]) under short exposure times (within hours of exposure). Body dehydration, however, may take a longer time (days of sustained heat) to reach its safe limit value with noticeable health effects. Health effects will worsen if both increases in body core temperature and dehydration are combined under hot exposure conditions. There are, however, other specific heat-related health indicators, particularly those indicators related to older occupants with pre-existing chronic illnesses (such as cardiovascular and respiratory diseases, diabetes mellitus, obesity, dementia, etc.). Among these indicators are blood pressure, blood glucose in diabetes, heart rate, cerebral blood flow, respiratory distress, behavioral change (agitation) of people with dementia, etc. There are very limited studies addressing this topic of research with inconclusive evidence for practical and general usage [78], and further work is needed to cover at-risk individuals with various types of pre-existing medical conditions.

The overheating limit criteria in LTCH are developed for older residents in good health conditions based on a simplified bioheat model and some assumptions of resident behavior during overheating events. One of the main assumptions is that residents are assumed to rehydrate themselves by regularly drinking water to replace up to 80% of the water loss by sweating during overheating events (assuming drinkable water is available in typical indoor settings of LTCH). However, as the vast majority (90%) of older residents of LTCH have some kind of pre-existing medical conditions [11], the developed criteria should be used with caution for these types of occupants or be made more stringent upon the availability of real-life evidence on rehydration rates. One way to make the criteria more stringent is to assume a lower rehydration rate, and the corresponding limit criteria are deduced from the regression lines of Figures 8 and 9.

It should be noted that the overheating limit criteria (Equation (6)) are applied to indoor overheating events as identified by the procedure in Section 2.4.1. Although overheating events follow outdoor heat waves, they are different in terms of their attributes (duration, intensity, and severity). Overheating events may start before and end days after outdoor heat wave events and may become severe even with mild outdoor heat waves due to internal heat buildup from casual internal gains and solar radiation. It is, therefore, important to consider all possible overheating events during a summer period, not only the ones resulting from extreme outdoor heat waves, to apply the limit criteria and declare overheating.

The aforementioned overheating limit criteria will need to be validated in real settings. However, standard benchmark cases (by simulation or field measurement) are not available. This study suggests as a benchmark to use long-term (over the duration of overheating events) building occupant satisfaction survey data on overall thermal comfort and heat-related health symptoms in field studies. In simulation benchmark studies where health symptoms are not available, suitable thermal comfort models should be used for this purpose, assuming comfortable conditions are associated with minimum health effects for healthy occupants (note the situation may be different for sick occupants).

Comparison of the proposed method of overheating with those based on comfort indicators and ad hoc limit criteria such as TM52, PHI, and BC revealed a weak relationship between them, being dependent on local climate, building construction, and space operation, and therefore it is difficult to draw a general trend between them. This is expected for two reasons. First, the time domains to evaluate overheating risk of each method are different (duration of overheating event versus entire summer). The comfort-based methods evaluate overheating risk for all possible overheating events that might occur during the entire summer period. The individual effect of an extreme overheating event is therefore smoothed out. Second, the exposure conditions of occupants of both methods are different (personal exposure versus fixed-space exposure), resulting in significant differences between the two methods, particularly when occupants dwell in multiple and different spaces during a complete day (24 h) exposure (such as bedrooms and cool common spaces; Option CONC in Figure 11).

5. Conclusions

This paper developed a calibrated general model of LTCHs under the EnergyPlus software platform [37] to perform overheating risk analysis and develop limit criteria. The model was built from a real monitored building but with typical old and current construction practices in the chosen locality. The model was calibrated using the monitored indoor conditions data of the real building and published energy use intensity data of similar sets of old and recent buildings. A general approach was developed to evaluate overheating risk in buildings from the perspective of thermal comfort or heat-related health outcomes. The heat-related health approach was considered more appropriate for this study and was applied to the building model of LTCHs to develop overheating limit criteria to declare whether or not a building is safe for space occupancy under extreme heat events. The limit criteria are intended to be used in any simulation or field study to evaluate overheating risk in similar buildings in any Canadian location. The proposed overheating method was as well compared with selected comfort-based methods for the purpose to find a common background for both types of overheating limit criteria.

Two general models of LTCHs with similar geometry and orientation to the monitored building were developed to cover typical Canadian climates in five selected cities (Montreal, Ottawa, Toronto, Calgary, and Vancouver). The first general model represents buildings with typical old construction practices of the eighties (1980) at the chosen locality, but with a partial retrofit for the roof, HVAC and lighting systems and other equipment as per the requirements of the current building code NECB-2017. Other input data (such as air infiltration rate) were taken from published average data of a similar set of buildings. The second general model represents new buildings with the current construction practice at the chosen location. All the model input data were taken from the current NECB-2017 and published data on air leakage rates of recent buildings. The general models of LTCHs were calibrated using the measured conditions of indoor temperature and relative humidity of the monitored building, and published energy use intensity (EUI) data of similar real buildings. The thermal calibration of the models showed very good agreement between the model predictions and measured data for indoor temperature and relative humidity. Similarly, the energy calibration of the models showed that the predicted EUI was within the range of the published data of real buildings.

A general approach was developed to evaluate overheating risk in buildings from the perspective of thermal comfort or heat-related health effects on building occupants. Evaluation of overheating risk using comfort indicators applied to fixed spaces does not account for the cumulative effect of heat on building occupants from day to day during heat wave periods. However, the approach that uses the heat-related health indicators accounts for all occupied spaces during a full-day exposure, and therefore the cumulative effect of heat on occupants' health is carried over from day to day. In this study, heat-related health indicators were used to develop overheating limit criteria for safe building occupancy during heat waves. This approach requires that the attributes of the indoor overheating events resulting from outdoor heat waves in terms of duration (DUR), intensity (INT) and severity (SETH) shall be capped to avoid any health injury to building occupants. The health indicators included body dehydration from sweating and inadequate water replacement and maximum body core temperature. These indicators were selected because they were the main causes of mortality in previous large-scale extreme heat events such as the European 2003 heat wave [55]. The overheating limit criteria were obtained by correlating the duration (DUR), severity (SETH), and intensity (INT) of overheating events to the aforementioned cumulative body water loss (dehydration) and maximum body core temperature. Body dehydration and core temperature were calculated using simplified two-node bioheat models for young and older people [70,71]. Overheating is declared if any of the three limit criteria is exceeded in any given space or entire building space.

Comparison of the proposed method of overheating with those based on comfort indicators and ad hoc limit criteria such as TM52, PHI and BC Housing for a case study with mild summer revealed a disparity between them in predicting the level of space overheating. When compared against the overall thermal comfort (a proxy of overall occupant satisfaction with indoor conditions), the proposed method showed consistent results in contrast to the other methods having stringent requirements for overheating risk declaration. Furthermore, the relationship between the proposed and the comfort-based methods is very weak, particularly when occupants dwell in multiple and different spaces during a complete day (24 h) exposure (such as bedrooms and cool common spaces). It is therefore difficult to consolidate the comfort-based criteria (HE or similar indicators) with equivalent health-based limit criteria that are applicable to any climate and building.

It should be noted that the overheating limit criteria of this study were developed for healthy older residents under typical cold climate locations with temperate summers. For older residents with pre-existing medical conditions, or for other warm and/or humid climates where residents are more likely acclimatized to heat and humidity, the limit criteria should be applied with caution pending further research.

Future work will include developing similar limit criteria for other vulnerable buildings, such as schools and senior homes with independent (minimum assistance) living styles.

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