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Cumulative Multi-Day Effect of Ambient Temperature on Thermal Behaviour of Buildings with Different Thermal Masses

Anna Staszczuk [1,*] **and Tadeusz Kuczyński** [2]

[1] Institute of Civil Engineering, University of Zielona Góra, Prof. Z. Szafrana Str. 1, 65-516 Zielona Góra, Poland
[2] Institute of Environmental Engineering, University of Zielona Góra, Prof. Z. Szafrana Str. 15, 65-516 Zielona Góra, Poland; t.kuczynski@iis.uz.zgora.pl
* Correspondence: a.staszczuk@ib.uz.zgora.pl

Abstract: In most studies, the effect of the thermal capacity of the building envelope on changes in internal temperatures is reduced to a 24 h period. During this period, daytime heat gains are balanced by nighttime heat losses. The maximum indoor temperature, the diurnal variation of the indoor temperature and the time lag between the occurrence of the maximum daily temperature determine the effect achieved. The aim of the article was to show that the effect of the thermal capacity of a building on the indoor temperature is not limited to 24 h but accumulates over a period of several days, mainly depending on the temperature and solar radiation history of the previous days. As a result, contrary to what some studies have suggested, the bedrooms of heavier buildings remained significantly colder at night during periods of prolonged high outdoor temperatures. The results obtained may fundamentally influence the perception of the effect of using the high thermal capacity of the building envelope to reduce high indoor temperatures in hot weather.

Keywords: thermal mass; building overheating; heat wave; energy storage

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1. Introduction

1.1. State of the Art

For many decades, attempts have been made to improve the methodology for performing an energy audit of buildings to take into account the complexity of their operation, the materials from which they are constructed, the heating and cooling systems used, the interaction with the external climate or the behaviour of the users [1]. Equations [2,3] and simulation tools [4,5] have been proposed to assess the overall energy performance of buildings. However, describing the thermal characteristics of buildings with specific indices or ratios has not yielded satisfactory results. Indices such as envelope thermal insulation, heat transfer coefficient, uncontrolled air infiltration coefficient or solar heat gain coefficient (SHGC) often insufficiently approximate the thermal behaviour of a building in both winter and summer conditions [1]. The thermal behaviour of a building is also significantly influenced by its thermal mass. At least since the 1970s, attempts have been made to quantify this relationship. In the late 1970s, Yu [6] introduced the concept of the M-factor, which expresses the ratio of the dynamic heat flux of a masonry wall to its theoretical steady-state values and proposed it as a factor that takes into account its thermal capacity, a correction factor to the steady-state wall heat conduction equation [7]. The M-factor was included in the US design guidelines and was immediately met with severe criticism and attempts to have it removed [8–10]. A comprehensive review of the reliability of the M-factor has been presented by Godfrey et al. [10]. In their opinion, it has no technical justification but this does not mean that the thermal capacity does not have an impact on the thermal behaviour of the building. It seems unreasonable to focus only on the walls of the building, when in fact the thermal behaviour depends on many other factors related to its construction, materials, heat transfer pathways, external climate, heating and cooling control strategies, or occupant behaviour. Consequently, the introduction of a factor attributed to only one of the elements of a complex system, i.e., a building in use, cannot reflect the real conditions of its functioning [10]. Consequently, the authors recommended that the "M" factor be removed from norms and standards. Attempts to find simplified methods that would allow a sufficiently accurate energy audit based on the description of selected envelope properties and possibly climatic conditions have been made by Altermann et al. [11], Robinson et al. [12], Reilly and Kinnane [13], and Arkar and Perino [14]. Al Sanea et al. [15] introduced the concept of dynamic envelope thermal resistance. For the unidirectional heat flow, which we are dealing with in summer (towards the inside of the building) or in winter (towards the outside of the building), its value does not differ from the value of the standard coefficient. In the transitional months with moderate temperatures, when the direction of the heat flow changes during the day, the magnitude of the dynamic thermal resistance of the envelope increases with the increasing thermal inertia of the envelope and reaches an asymptotically constant value at a correspondingly high value. In order to ensure that buildings are adequately protected from overheating under conditions of high summer temperatures, Di Perna et al. [16] proposed that the values of the maximum instantaneous heat transfer coefficients for external walls should depend on their thermal capacity. The use of high thermal capacity materials, with the exception of PCMs, to decrease indoor temperatures in hot weather is currently not a widely recommended strategy [17,18]. Among the 20 passive cooling strategies analysed by Díaz-López et al. for schools in Spain, the use of heavy building materials was not included [17].

There is an even more cautious approach to the use of high thermal mass building envelopes in temperate and cold climates. Dodoo [19] considers the use of external blinds and night ventilation as key passive techniques that can protect residential buildings in Sweden from the effects of rising temperatures over the next 40 years, not to mention the potential benefits that increased thermal capacity can bring. Finney [20] concludes from his experience in the design, construction, and operation of high and low thermal capacity dwellings that heavy buildings consume more heating energy than light ones. Tuohy et al. [21] dispute this finding, pointing out that his observations were based on pre-1976 buildings with poor insulation, airtightness, and significant thermal bridging. Reilly and Kinnane [13], on the other hand, point out that the high thermal capacity of buildings is often considered an important and beneficial feature of buildings, and that it is often given an overly large role in shaping the microclimate of a building compared to the thermal insulation of its envelope. At the same time, they note that the effect of the thermal mass of the building envelope is very poorly quantified in the existing scientific literature. They recommend the use of transient energy demand analysis, which they claim allows the effect of thermal mass to be quantified, taking into account the thermal insulation of partitions. The simulation studies that they carried out using this method for the summer climate of Madrid (hot with high daily air temperature variations during the day and intermittent use of buildings) confirm many previous reports in the existing scientific literature on the beneficial effect of high thermal mass on the thermal conditions of buildings in this type of climate. At the same time, they suggest that the high thermal capacity of the building envelope may be unfavourable in colder climates where heating is the predominant problem. They suggest that, in cold climates, it may be more advantageous to place thermal insulation on the internal surfaces of high thermal mass building walls rather than on their external surfaces, thereby reducing the thermal capacity of the building. In summary, they conclude that the design objective in cold climates should be to reduce, rather than increase, the thermal mass within the insulation of the building to ensure the most favourable equivalent thermal conductivity value.

The heat transfer between a building and the outside air depends primarily, primarily on the thermal conductivity of its envelope, as mentioned above. However, the thermal inertia of all its envelopes also has an important influence on the magnitude and time course of this phenomenon, allowing it to store thermal energy and delay the time of its release to the indoor air [22]. Soil thermal accumulation and high soil thermal inertia may stabilise internal air temperature and the temperature of compartments that directly touch soil [23,24].

Childs [8], in analysing the effect of the thermal capacity of a building in which no heating or cooling is expected to be used, states that such an effect can then be limited to changes in the magnitude of the diurnal variation of internal temperature and its distribution over a 24 h period. Similarly, the thermal inertia of a building is related to its thermal performance by most other authors, who tend to consider three parameters as the most relevant: the decrement factor, the time lag [25–28], and the reduction of peak temperatures at the hottest times of the day [29–31]. While the decrement factor is understood as the degree by which the diurnal variation of the indoor temperature decreases with respect to the outdoor temperature, the time lag describes how much the occurrence of the maximum indoor temperature is delayed with respect to the outdoor temperature. These two parameters in turn depend on the density, thermal capacity, and thermal conductivity of the materials from which the partitions are made [32,33]. The quotient of the thermal conductivity of a material by the ratio of its density to its thermal capacity is called thermal diffusivity. It measures the ability of a material to conduct thermal energy relative to its ability to store it [34] and is a key element in determining the thermal behaviour of materials and the structures made from them [35]. Thermal diffusivity can be considered a measure of the thermal inertia of a material or structural element, as its value increases with increasing thermal conductivity relative to thermal capacity [36]. Stephan et al. [22] argue that when analysing the effect of thermal inertia on the thermal performance of a building, attention should be paid to the level of air exchange between the space and the external environment [37,38], as well as the magnitude of external [26,39] and internal [16] thermal loads.

When discussing the potential benefits of increasing the thermal mass of the building envelope during prolonged and severe heat waves in temperate climates, it is worth noting that unlike other passive techniques recommended for this purpose, such as night ventilation or external solar shading, this method does not require the active involvement of the occupants, whose behaviour is often far from what is expected.

A UK study of windows opening during high outdoor temperatures found that it was often quite different from was expected, with south-facing windows remaining closed during a hot summer night [40–42]. According to the authors, this may be due to street noise, outdoor pollution, or safety considerations, particularly in ground floor bedrooms. In many buildings, the ventilation system itself was limited: for example, windows were too difficult to open [43]. The same can be said of blinds, which are closed much less often than they need to be in hot weather conditions. Zuurbier et al. [44], showed in a study of 113 retirement homes that there was virtually no increase in the frequency of shutter closures at high outside temperatures. In addition, homes in temperate climates tend to use interior blinds, which are not very effective against high temperatures. According to Clery et al. [45], while 25% of UK households use internal blinds in the summer heat, only 4% use the much more protective external blinds. Van den Wymelenberg [46] states that there is not enough knowledge about how people operate blinds and what motivates them. There is even less knowledge about this than about opening windows. Another study, conducted in London’s first new Passivhaus certified apartment, found that residents used blinds more than expected in winter (for privacy) and less than expected in summer (because they did not want to sacrifice views). As a result, summer temperatures were higher than expected, but this did not lead to changes in occupant behaviour [47].

According to Borghero et al. [48], preventing excessive temperatures is more likely to be influenced by user behaviour than by retrofitting.

1.2. Main Goal of the Study

In most analyses, the effect of the high thermal capacity of the building envelope on the level and temporal distribution of indoor temperatures is limited to a 24 h period. It is assumed that during the day it accumulates heat mainly from the outside air and solar radiation, reducing the maximum internal temperature and increasing the time lag. At night, the heat stored in the building envelope is released to the air inside the building, increasing its temperature [29–31,49].

The aim of the study was to determine how consecutive days with increasing or decreasing outdoor temperatures affect the difference between the maximum day temperature and the minimum night temperature in a building with low and high thermal capacity. The study was carried out during the transition period and during a summer heat wave.

1.3. Novelty of the Work

The novelty of the work was to demonstrate experimentally that the effect of a building's thermal mass on its internal temperature is not limited to a single day and is not limited to the effects of changes in peak temperature, decrement factor, and time lag [50,51]. As the outdoor temperature increases or decreases on successive days, the temperature difference between a light and heavy building increases or decreases accordingly.

The study also showed that the cumulative multi-day effect of increasing outdoor temperatures on the temperature difference between light and mediumweight buildings during heat waves exceeds that of a 24 h cycle. As a result, and contrary to what the results of some studies suggest [49], bedrooms in heavier buildings remained significantly cooler at night during periods of prolonged high outdoor temperatures. The difference between the peak daytime temperatures in both building increased over successive days of increasing outdoor temperatures.

The research was carried out in two real free-standing residential buildings, differing only in the thermal capacity of the walls, whereas most research in this area has been carried out in free-standing experimental facilities, usually much smaller and sometimes close to real facilities [52–54], or in climatic chambers in a fully controlled environment [51,55]. Such rooms do not fully reflect real conditions, as their thermal performance depends not only on their thermal capacity but also on the thermal capacity of the whole building, which is much higher.

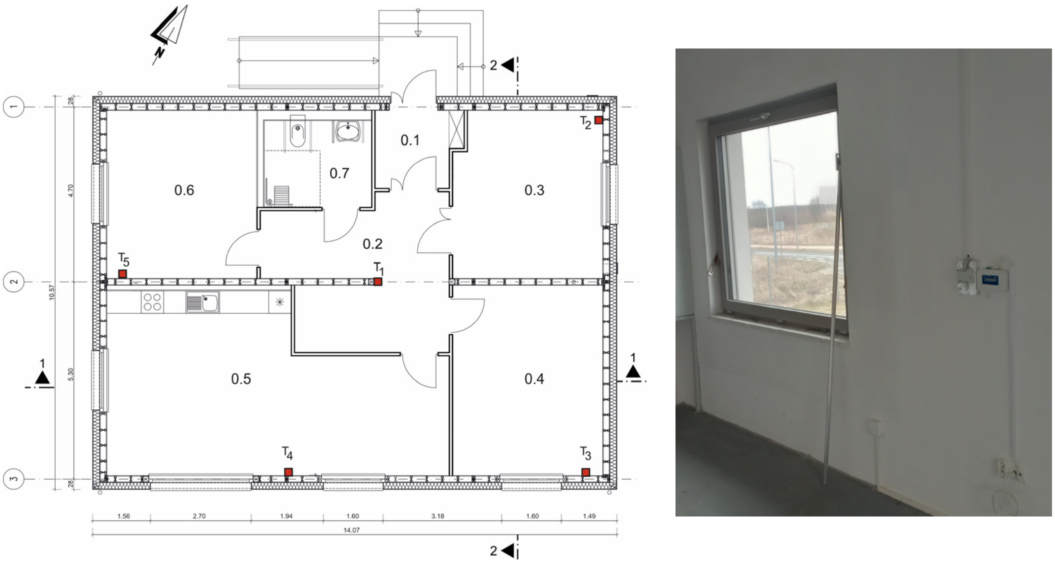
2. Materials and Methods

2.1. Characteristics of Experimental Buildings

The research was carried out on two full-scale objects, experimental buildings designed to be almost identical with except for the construction of their external and internal walls: building B1 (on the left in Figure 1), a traditional masonry construction, and building B2 (on the right in Figure 1) a lightweight skeletal construction with both external and internal timber-framed walls.

Figure 1. Experimental buildings.

These buildings were located in the Science and Technology Park of the University of Zielona Góra in Nowy Kisielin—a small district in the city of Zielona Góra in Poland (with a Cfb climate, according to [56]). The buildings have the same main façade orientation, similar floor areas (122 m^2), and identical room layouts (Figure 2). They were unoccupied and unfurnished to maintain the same boundary conditions for experiments.



(**a**) (**b**)

Figure 2. Plan of the building B2 (**a**) with location of thermo-hygrometers (**a**,**b**).

The detailed data of their construction solutions, thermal properties, and materials are presented in Tables 1–5.

Table 1. Construction components of experimental building B1.

Component	Material	Thickness (cm)
External wall	Lime sand plaster	1
	Cellular concrete blocks	24
	Mineral wool (90)	20
	Cement lime plaster	1
Internal wall 1—construction wall	Lime sand plaster	1
	Lime sand blocks (silicate)	24
	Lime sand plaster	1
Internal wall 1—partiton wall	Lime sand plaster	1
	Lime sand blocks (silicate)	8
	Lime sand plaster	1
Ceiling	Mineral wool (40)	2 × 20
	Oriented strand board	2.2
	PE membrane	
	Distance frame for gypsum board	20
	Gypsum board	1.25
Slab on ground	Concrete screed layer	5.5
	PEHD membrane	
	Mineral wool (150)	30
	Asphalt	
	Concrete slab	15
	Sand ballast	30
	Surrounding ground	

Table 1. *Cont.*

Component	Material	Thickness (cm)
Foundation wall	Concrete blocks	24
	EPS	20

Table 2. Construction components of experimental building B2.

Component	Material	Thickness (cm)
External wall	Fermacell gypsum fibreboard	1.5
	Oriented strand board	1.5
	Mineral wool (40)—section a	16
	Pine wood beam—section b	4.5 × 16
	Oriented strand board	1.5
	Mineral wool (90)	18
	Cement lime plaster	1
Internal wall 1—construction wall	Fermacell gypsum fibreboard	1.5
	Oriented strand board	1.5
	Mineral wool (40)—section a	16
	Pine wood beam—section b	4.5 × 16
	Oriented strand board	1.5
	Fermacell gypsum fibreboard	1.5
Internal wall 1—partition wall	Gypsum board	2 × 1.25
	Mineral wool (90)—section a	5
	Steel framed structure—section b	
	Gypsum board	2 × 1.25
Ceiling	Mineral wool (40)	16
	Oriented strand board—section a	1.8
	Mineral wool (40)—section a	26
	Ceiling beam—section b	8.9 × 30
	Oriented strand board—section b	1.8
	PE membrane	
	Fermacell gypsum fibreboard	1.25
Slab on ground	Concrete screed layer	5.5
	PEHD membrane	
	Mineral wool (150)	30
	Asphalt	
	Concrete slab	15
	Sand ballast	30
	Surrounding ground	
Foundation wall	Concrete blocks	24
	EPS	20

Table 3. Construction components of windows and doors in experimental buildings.

Component	Construction, Properties
Windows 1—SK	System Passive Line Plus Glazing: 4TM/18A/4/18A/4TM—48 mm $Ug = 0.5\ W/m^2K$; $g = 50\%$; $L_t = 72\%$; $U_w = 0.709\ W/m^2K$ SHGC (av.) = 0.50 Total dimensions: 1.6 m × 1.47 m

Table 3. *Cont.*

Component	Construction, Properties
Windows 3—SK	System Passive Line Plus Glazing: 4TM/18A/4/18A/4TM—48 mm Ug = 0.5 W/m^{2}K; g = 50%; L$_t$ = 72%; U$_w$ = 0.74 W/m^{2}K SHGC (av.) = 0.50 Total dimensions: 2.7 m × 2.22 m
Internal door	S900—82.5 mm PVC panel Internal dimensions: 1.2 m × 2.0 m; U$_w$ = 0.78 W/m^{2}K Total dimensions: 1.42 m × 2.09 m
External door	Wing 68 mm; GRP panel/ urethane foam/GRP panel U$_d$ = 0.76 W/m^{2}K Total dimensions: 1.60 m × 2.20 m

Table 4. Thermal properties of building components.

Component	Building B1		Building B2	
	κ_m [kJ/m^{2}K]	A [m^2]	κ_m [kJ/m^{2}K]	A [m^2]
External wall	97.00	116	37.33	116
Internal wall 1	416.00	34	74.66	34
Internal wall 2	160.00	62	45.00	62
Ceiling	11.25	122	17.30	123
Slab on ground	92.40	122	92.40	123

Table 5. Thermophysical properties of building materials.

Material	λ (W/m K)	ρ (kg/m^3)	c (J/kg K)
Asphalt	0.8	1000	1460
Cellular concrete blocks	0.16	600	1500
Lime sand plaster	0.82	1850	840
Concrete screed layer	1.15	1800	1000
Concrete slab	1.35	2000	1000
Ceiling beam	0.3	500	1000
Fermacell gypsum fibreboard	0.32	1153	1200
Gypsum board	0.25	900	1000
Cement lime plaster	0.8	1600	1000
Lime sand blocks (silicate)	0.55	1600	1000
Mineral wool (40)	0.036	40	1030
Mineral wool (90)	0.037	90	1030
Mineral wool (150)	0.04	150	1030
EPS	0.031	100	1450
Oriented strand board	0.13	650	1700
PE membrane	0.33	920	2200
PEHD membrane	0.5	980	1800
Pine wood beam	0.16	550	2510
Sand ballast	0.4	1650	840

The thermal heat capacity (κ_m) was calculated according to ISO 13786 [57] and used to determine the TMP variable (thermal mass parameter), which characterises the thermal mass of the building according to the following formula [58]:

$$\mathrm{TMP} = \frac{\sum \kappa_m \cdot A}{\mathrm{TFA}} \tag{1}$$

where A is the area of the building's partition and TFA is the total floor area.

The heat capacity encompasses all walls (both external and internal), floors, and roofs bounding the experimental buildings B1 and B2 (Table 4).

The values of TMP for the analysed buildings are B1 = 400 $\mathrm{kJ/m^2K}$ and B2 = 192 $\mathrm{kJ/m^2K}$, and these buildings are classified as mediumweight and lightweight, respectively.

2.2. Measurements

The research was carried out during the spring and summer of 2015 to 2018. Air temperature and relative humidity were recorded inside the test rooms, and outdoor parameters, such as air temperature, relative humidity, and global horizontal solar radiation, were recorded continuously. The technical specifications of the measuring devices are presented in Table 6.

Table 6. Technical specifications of measuring devices.

Measuring Device	Measurement Parameter	Measuring Range	Accuracy/Error
P18—temperature and humidity transmitter. The installation location is shown in Figure 2. Installed at a height of 1.2 m above the floor surface.	Temperature of indoor air Humidity of indoor air	−30 . . . −20 . . . 60 . . . 80 °C 0. . .100%	±0.5% ±2% dla RH = 10 . . . 90% ±3% dla RH otherwise
Delta OHM, type HD9008TRR	Temperature of outdoor air	−40. . . +80 °C	±0.15 °C ±0.1% measured value
Shielded Delta OHM, type HD9007A1	Relative humidity of outdoor air	0. . .100%	1.5% RH (0. . .90%RH) ±2.0% RH otherwise
Delta OHM, type LP PYRA 03	Global solar radiation	0 ÷ 2000 $\mathrm{W/m^2}$	Sensitivity: 5–15 $\mu\mathrm{V/Wm^2}$ Annual stability: $<|\pm 2.5|$% Nonlinearity: $<|\pm 2|$% Directional error: $<|\pm 22|\ \mathrm{W/m^2}$

The equipment for measuring outdoor climate parameters is located on the roof of building B1.

Indoor air temperatures in the laboratory buildings were measured at five measuring points (Figure 2) and then averaged per area. Measuring point T_1 covers temperatures in Rooms 0.1, 0.2, and 0.7, while T_2 covers Room 0.3, T_3 covers Room 0.4, T_4 covers Room 0.5, and T_5 covers Room 0.6. The areas of the rooms were taken into account accordingly. Regular measurements of all above mentioned parameters have been taken since June 2015 and have been recorded in the BMS (building management system) every 5 min.

The basic experimental research presented in this article concerns the period from 13 to 23 May 2016. During this period, both buildings maintained the same boundary conditions. In addition, the results of measurements related to the extremely intense heat wave of the summer of 2018 are considered in this paper. In all rooms, the air exchange was kept constant at 0.6 per hour, slightly above the recommended minimum value of 0.5 per hour [59,60]. The blinds on the windows were left open, reflecting the typical conditions of use of residential buildings in Poland during the summer. The buildings were mechanically ventilated and controlled with an anemometer.

3. Results and Their Discussion

Figure 3 shows the evolution of temperatures in buildings B1 and B2, consisting of three bedrooms, with windows facing east (Room 0.3), south (Room 0.4), and west (Room 0.6), and a living room with windows facing south and west (Room 0.5). The daily temperature patterns in the rooms of both buildings are shown with their values averaged every 10 min for the period 13–23 May 2016.

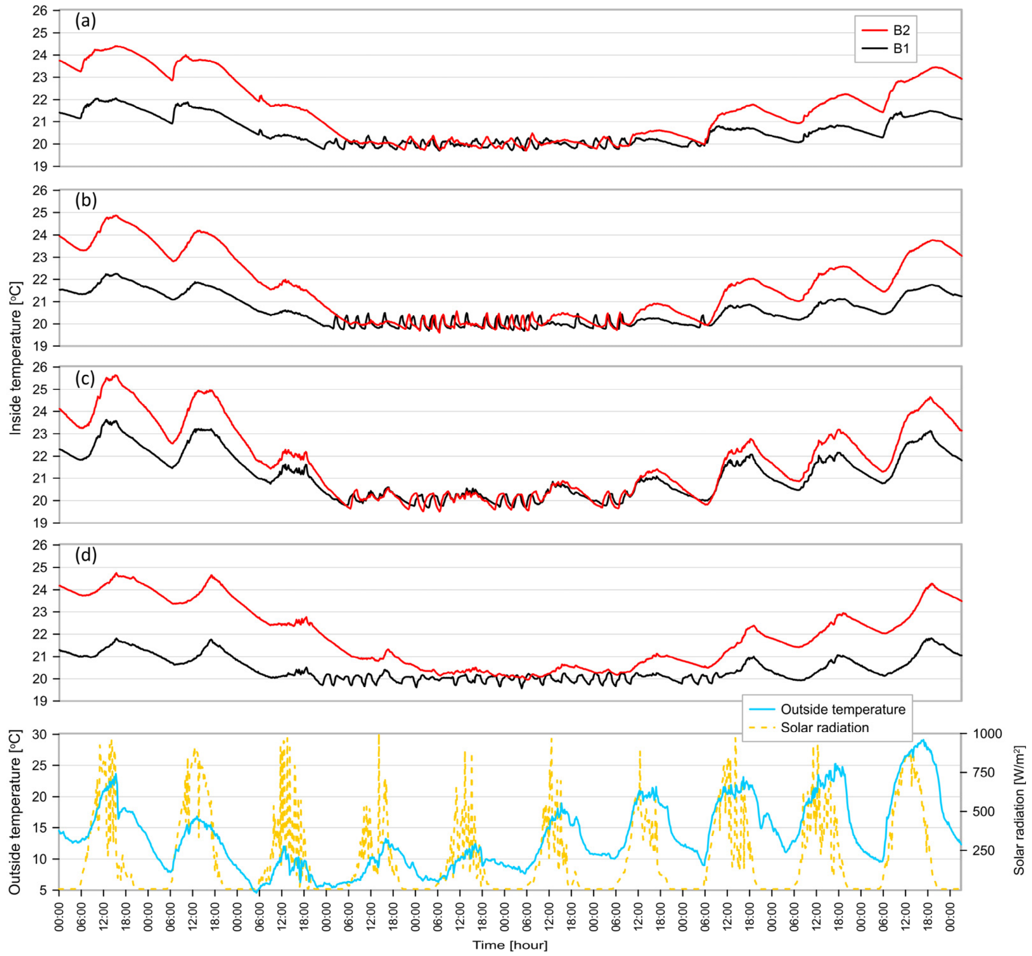


Figure 3. Temperature courses in lightweight (B2) and mediumweight (B1) buildings on 13–23 May 2016; (**a**) bedroom with windows facing east (Room 0.3); (**b**) bedroom with windows facing south (Room 0.4); (**c**) living room with windows facing south and west (Room 0.5); (**d**) bedroom with windows facing west (Room 0.6).

During the first 3 days, the outside temperature decreased, causing the temperatures in the study rooms in both buildings to fall below 20 °C, thus activating additional heating. During this period, the average temperature difference between the corresponding rooms in both buildings decreased from an average of 1.9–3.0 K to 0–0.5 K. With the heating on, the temperature in the corresponding rooms was virtually the same. After five days, the increase in outdoor temperature made the additional heating unnecessary.

The next three days of rapidly rising outdoor temperatures caused the average temperature difference between the two rooms from to increase from around 0–0.5 K to 2.5 K.

The analysis of the graphs of the temperature history in the rooms of the buildings shown in Figure 3 clearly shows that the effect of the thermal capacity of the walls is not limited to one day.

Over a 24 h period, in the building with rooms of higher thermal capacity, there was a significant reduction in the maximum room temperature during the day and a reduction in the daily temperature variations compared to the building with lightweight walls. No phase shift of temperatures was observed in the corresponding rooms in either building. The results of the study show that during the period when the outdoor temperature increases significantly, the temperature difference between the rooms of the lightweight and the mediumweight building also increases systematically. In a short period of 1 to 4 days, a process takes place in which the difference between the temperatures of the rooms with low and high thermal capacity is not determined by the diurnal variation of the outdoor temperature and solar radiation but by the cumulative effect of their past. Similarly, when the outdoor temperature drops rapidly, the temperature difference between the respective rooms in the two buildings decreases from 2–3 K to 0–1.5 K, depending on the location of the room in relation to the direction that they face. While Figure 3 illustrates the evolution of the indoor temperature during the spring of 2016 with rapidly changing external climatic conditions, such as air temperature and solar radiation, Figure 4 shows the phenomenon of the increasing difference between the indoor temperatures in the living rooms of the two buildings studied during an extremely intense and prolonged heat wave that lasted from the third decade of July to the end of the first decade of August 2018.

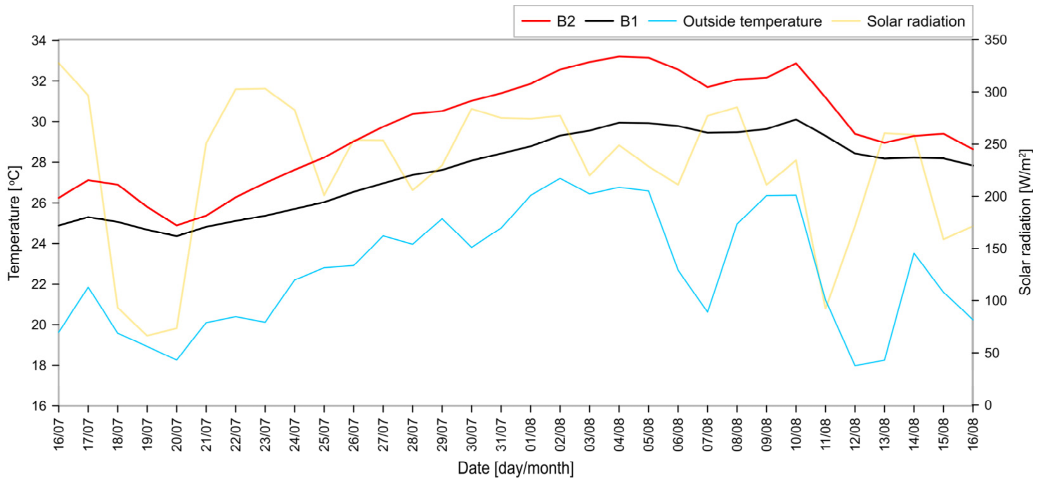


Figure 4. Average daily temperatures in the living room with windows facing south and west in lightweight (B2) and mediumweight (B1) buildings from 16 July–16 August 2018.

The figure shows the evolution of the average daily temperatures in a living room with south- and west-facing windows in buildings B1 and B2 during the warmest period of 2018, which included the prolonged and intense heat wave of the third week of July and the first week of August 2018.

Over the course of almost three weeks of steadily increasing outdoor temperatures, the difference between the indoor temperature in a building with low and medium wall thermal capacities increased from about 0.5 K to 3.3 K. In each of the periods considered, the greatest cooling effect of the high wall thermal capacities occurred during the highest outdoor temperatures, when it was most needed. This effect ranged from 2 K to 3.3 K and depended mainly on the evolution of the outdoor temperature and the intensity of solar radiation of not only the current day but also of the previous days.

Figure 5 shows the hourly temperature pattern for whole buildings B1 and B2 during the heat wave period from 19 July to 12 August 2018. The figure shows the patterns of hourly temperatures for all rooms in buildings B1 and B2. During almost 3 weeks of continuously increasing outdoor temperatures, the difference between the daytime room temperature in the building with light and heavy walls systematically increased from about 0.7 K to 3.5 K during this period. In each of the periods considered, the greatest cooling effect of the high thermal capacity walls occurred at the highest outside temperatures, when it was most needed. The magnitude of the differences in peak temperatures achieved in the low- and mediumweight rooms was closely related to the trend of changes in outdoor temperature and solar irradiance on consecutive days.

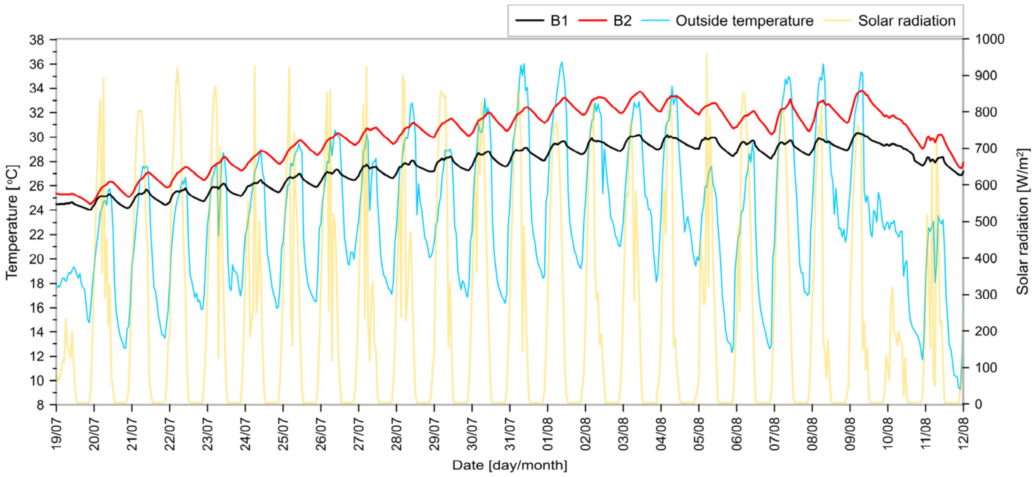


Figure 5. Hourly average temperatures in lightweight (B2) and mediumweight (B1) buildings from 19 July to 12 August 2018.

The differences between room temperatures in buildings B2 and B1 were generally higher during the day than at night, with the temperature in building B2 always higher than in B1 even at night.

Conclusions similar to those presented in this paper have been reached by analysing the graphs of temperature courses in studies conducted over a longer period of time [61–63]. In addition to the diurnal effects expressed in terms of time lag and the damping factor, increasing the thermal mass had the effect of increasing the temperature difference between the studied rooms [61,63], maintaining a significant temperature difference between them even at night [27], and increasing and decreasing the temperature successively over periods of several days [62].

These results contradict certain other research findings, which found that the effectiveness of using high thermal mass materials in buildings is generally linked to the simultaneous effect of night ventilation, which would allow the removal of excess heat stored in solid partitions during the hot day [64–67]. Some authors point out that the effectiveness of high thermal mass partitions in bedrooms, where there is a concern that heat released at night may affect sleep comfort, needs to be supported by night ventilation of up to 10 ACH [68–70]. In addition to the diurnal effects in the form of an increase in the time lag, a decrease in the growth rate and a decrease in the peak temperatures at the hottest times of the day, an increase in thermal mass also causes a progressive increase in temperature differences that persist over many days and are maintained not only during the day but also at night. At the same time, the magnitude of the differences in peak temperatures achieved in lightweight and heavyweight (or mediumweight) mass spaces is closely related to the direction, magnitude, and duration of changes in outdoor temperature.

Tink et al. [70] conducted a study in a semi-detached brick house built around 1910 in a rural village in Leicestershire, UK. One of the houses had 0.23 m thick brick walls insulated internally with 0.065 m air gap phenolic boards and plasterboard. Both houses were unoccupied and had no furnishings other than equipment for monitoring and synthesising occupancy. The study was conducted from 5 June to 3 July 2015 for the unheated buildings. Throughout the measurement period, the average air temperatures were 2.2 K higher in the living room and 1.8 K higher in the bedrooms in the insulated rooms, where the thermal capacity of the walls was cut off from the interior. The higher temperatures in the insulated building were maintained both during the day and at night, and the difference between them, although decreasing at night, systematically increased over time.

Brambila and Jusselme [71], in an experimental study conducted from 10 to 21 August 2016 in Freiburg, Switzerland, in two detached rooms with internal dimensions of 6.3 m × 3.2 m × 3.1 m, typical of a two-person office in Switzerland, showed that high thermal mass was most effective in reducing the internal temperature when combined with night ventilation but also remained effective in its absence. The analysis of the temperature history graphs shows that, for at least two consecutive days, the temperature difference between the heavy and light structures increased as the outside temperature increased and decreased as the outside temperature decreased. Throughout the study period, the temperature in the light room remained significantly higher than in the heavy room, with the differences being greater during the day than at night.

Grynning et al. [31] investigated the effect of floor thermal capacity on indoor temperatures on hot days. The study was conducted during a heat wave in June/July 2018 in a specially constructed room in an experimental zero-energy building in Trondheim, Norway. The building consisted of two identical rooms with dimensions of 2.4 m × 4.2 m × 3.3 m. Tests conducted with the ventilation closed showed that the average daytime maximum temperature in the room with the concrete floor was about 2.5 K (10%) lower, while the average nighttime minimum temperature was about 1.5% higher than in the room with the wooden floor. An analysis of the temperature curves included in the paper shows that the differences between the temperatures in the two rooms increased as the outdoor temperature rose on consecutive days and decreased as it gradually fell.

4. Conclusions

This paper demonstrates experimentally that the effect of a building's thermal mass on its internal temperature is not limited to a 24-h period and, as suggested by many authors, to changes in peak temperature, decrement factor, and time lag. Under conditions of high solar radiation, when the external temperature increases on successive days, the difference between the temperatures of a building with a low mass and a building with a medium mass also increases. Conversely, the difference between the temperatures in the low and medium mass buildings decreases when the outdoor temperature decreases.

This study also found that the cumulative multi-day effect of rising outdoor temperatures on the difference between light- and mediumweight buildings during heat waves was more significant than its dependence on the 24 h cycle. Contrary to the results of some experimental and modelling studies and analyses of theoretical models, bedrooms in heavier buildings remained significantly cooler at night even during prolonged heat waves. These effects occurred despite the fact that minimum ventilation rates were maintained at the minimum level required for sanitary reasons, with no additional night ventilation, which, according to numerous studies, should result in a reduced ability to remove heat from the building to the outside air at night, leading to excessive temperatures in sleeping areas, where maintaining low temperatures is particularly important for occupant comfort. The difference between the minimum nighttime temperature and the maximum daytime temperature in the mediumweight–heavyweight building increased steadily on successive days of rising outdoor temperatures compared to the lightweight building. On the hottest days, the high thermal capacity building had a minimum night temperature of 2.5–3 K lower and a maximum day temperature 3.5 K lower than the lightweight building.

The analysis presented in this article is based on experimental results obtained in real buildings. The results obtained may influence the perception of the effect of using traditional building materials with high thermal inertia in the building envelope to reduce indoor temperatures during severe and prolonged heat waves, demonstrating that they have a beneficial effect both during the day and at night and that this effect improves as the outdoor temperature rises and the intensity of solar radiation remains high on successive days of a heat wave.

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