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Climate change induced heat stress impact on workplace productivity in a net zero-carbon timber building towards the end of the century

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Abstract

Changing climate intensifies heat stress, resulting in a greater risk of workplace productivity decline in timber office buildings with low internal thermal mass. The impact of climate change induced heat exposure on indoor workplace productivity in timber office buildings has not been extensively researched. Therefore, further investigation to reduce the work capacity decline towards the end of the century is needed. Here, heat exposure in a net zero-carbon timber building near Brussels, Belgium, was evaluated using a reproducible comparative approach with different internal thermal mass levels. The analysis indicated that strategies with increased thermal mass were more effective in limiting the effects of heat exposure on workplace productivity. The medium and high thermal mass strategies reduced workplace productivity loss to 0.1% in the current, 0.3% and 0.2% in the midfuture, and 4.9% and 3.9% for future scenarios. In comparison, baseline with low thermal mass yielded a decline of 2.3%, 3.3%, and 8.2%. The variation in maximum and minimum wet-bulb globe temperatures were also lower for medium and high thermal mass strategies than for low thermal mass baseline. The study findings lead to the formulation of design guidelines, identification of research gaps, and recommendations for future work.

Keywords

heat exposure
office buildings
work capacity
thermal mass
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1 Introduction

Changing climates across the globe have had an unanticipated and unexpected impact on workplace productivity (Dasgupta et al. 2021). Climate change deteriorates workplace productivity due to extreme heat stress that makes work slower and requires more breaks to rehydrate, recover, and cool off (Kjellstrom et al. 2009; Parsons 2014). This will result in economic loss due to productivity decline and occupational health hazards (Kjellstrom et al. 2009). With the European Union's (EU) goals to significantly lower greenhouse gas (GHG) emissions and energy use by 2030 in the building sector, it is important to devise strategies that are carbon-neutral and energy-efficient for the building sector in the EU (Chatain 2023). Timber buildings are gaining prominence in the EU as an effective strategy to achieve these goals since they are renewable, climate neutral, and climate positive (Hurmekoski 2017). This report also found that timber constructions can lessen waste generated due to reduced material use, lower energy consumption, and CO_2 emissions from the production of construction products.

Timber construction has a lower environmental impact than conventional building sector practices, as reported in existing literature (Sathre and O'Connor 2010; Oliver et al. 2014; Wang et al. 2014). Currently, large number of multi-story timber building projects have been implemented in Europe including Germany, France, Sweden, which is likely due in part to the region's significant growth of cross-laminated timber (CLT) technology that is frequently used in many multi-story timber buildings (Salvadori 2017; Žegarac Leskovar and Premrov 2021). Europe is home to

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60 of the 84 timber constructions with eight or more floors based on data from the Council on Tall Buildings and Urban Habitat (Yu 2017; Logan 2023). Additionally, legislations have been passed in cities like Amsterdam in the Netherlands, where at least 20% of all residential constructions after 2025 will be using timber or other bio-based solutions (Beyda 2023). Furthermore, the European Commission is also considering adding requirements that measure the life cycle carbon emissions of construction materials and to develop renovation plans for buildings to decrease embodied carbon at country levels (Logan 2023).

However, despite the potential environmental benefits of timber buildings, they are susceptible to overheating due to their low thermal mass. This is significant since, according to studies from Seppänen et al. (2003), for every degree rise above 25 °C, performance at work falls by 2% on average. Overheating in buildings is significant since it directly correlates with heat exposure and workplace productivity. Studies from Attia and Gobin (2020) on a free-running timber dwelling in Belgium show the vulnerability of wooden construction to overheating for future scenarios. Furthermore, findings from Rodrigues et al. (2016) indicate that low thermal mass dwellings are more susceptible to overheating. The study tested the effectiveness of high-density fibreboards, along with phase change materials, to increase building thermal mass. The results showed an improved capacity in prefabricated timber buildings to regulate the internal thermal environment. Additionally, Dong et al. (2021) found that cross-laminated timber is more likely to overheat than concrete structures due to the various thermal masses. This was in line with findings from Pajek et al. (2017) that recommended enhancing lightweight timber buildings in Europe by incorporating materials with high thermal mass for an optimal thermal environment.

Findings from Adekunle and Nikolopoulou (2016) indicated that prefabricated timber housing had extreme summertime overheating for analysis using the Chartered Institution of Building Services Engineers (CIBSE) comfort model. Even in mild weather conditions, the risk of overheating was high due to the low thermal mass of the dwelling. Similar observations were found in studies like Roberz et al. (2017), with the lightweight building using significantly more cooling energy than the heavyweight and ultra-lightweight concrete building variants since it absorbs less solar and internal heat gains. In addition, the smallest temperature swing is seen in the case of a heavyweight building. Studies from Němeček and Kalousek (2015) also supported these findings and found that compared to typical brick buildings, wooden buildings without thermal mass overheat more. Similarly, studies like Albayyaa et al. (2019) and Kuczyński and Staszczuk (2020) found that dwellings with higher thermal mass performed better regarding cooling energy use than lightweight dwellings. The studies from Kuczyński and Staszczuk (2020) also recommended increasing thermal mass is effective even during extreme events like heat waves. To summarize the studies from existing literature, building thermal mass is recommended as an effective strategy to improve thermal comfort, reduce overheating, and better cooling energy use.

The analysis of existing literature indicated the following missing aspects. Firstly, most studies focus on the impact of varying levels of thermal mass on thermal comfort and energy use but do not consider its impact on workplace productivity. Secondly, even though thermal mass is recommended to improve overheating and energy use for current climate scenarios, it is also important to assess how varying levels of thermal mass will impact climate change induced heat stress in the future. Studying how the built environment in net zero-carbon timber buildings will behave in future extreme climates is equally important for carbon neutrality in the building sector. Therefore, the current study aims to bridge these missing aspects in the existing literature by assessing the effectiveness of internal thermal mass in reducing heat exposure and improving workplace productivity in a net zero-carbon timber building towards the end of the century in the mixed humid climates of Brussels.

The relevance of this study is based on the following aspects. Recently, Europe has been moving towards buildings that use low embodied carbon materials to comply with the Paris Agreement emission targets (Broer et al. 2022). A recent report from Röck et al. (2022) with case studies from five European countries, including Belgium, found that, on average, the amount of embodied carbon in a new building is 600 $kgCO_2e/m^2$, although this varies depending on the building and material choices. The report also indicated that 70% of this embodied carbon is released before the building's operation. Since many climate policies and reduction initiatives concentrate on operational carbon emissions, embodied carbon has long been an overlooked contributor (Broer et al. 2022). Therefore, this study focuses on a circular building with low embodied carbon that uses renewable, reusable, and recyclable materials (Al-Obaidy et al. 2022) and aligns with Europe's current trend. Additionally, the building can be demounted once its utility is completed, reducing wastage.

It is important to investigate the influence of heat stress on productivity in timber office environments because these buildings tend to have low thermal mass. Hence, timber buildings are more vulnerable to overheating, as from existing literature (Němeček and Kalousek 2015; Adekunle and Nikolopoulou 2016; Roberz et al. 2017). This will significantly impact the service industry in Europe in the age of digitalization, where a large market segment works in office spaces. Based on these observations, the study addressed the following research questions:

a. How will climate change induced heat exposure affect the indoor environment in a net zero-carbon timber building for varying internal thermal mass?
b. How will climate change induced heat exposure impact workplace productivity decline in a net zero-carbon timber building for varying internal thermal mass?

The main novelty of this study is based on its reproducible comparative approach with different internal thermal mass levels for the reference building and its effects on the built environment and workplace productivity. This was assessed using a whole-building energy performance simulation model and extreme climate scenarios. To the author's knowledge, this is one of the first attempts to provide evidence-based results and guidelines to climate change induced heat exposure and the decline in workplace productivity in net zero-carbon timber buildings towards the end of the century. This will enhance and support building designers and modelers in the early-stage design of net zero-carbon timber buildings. Additionally, this is a unique case study that promotes carbon-neutral, modular constructions with minimal embodied carbon. With advancements in embodied carbon benchmarking frameworks in Europe as per Broer et al. (2022), the study findings and proposed guidelines can contribute to these developments.

2 Methodology

The reference net zero-carbon timber building was developed using DesignBuilder v7.0.1, a graphical user interface for the EnergyPlus v9.6.0 simulation engine (Crawley et al. 2001). To create the energy performance simulation model, the relevant data on the reference building, such as weather, location, geometry, floor plans, Heating, Ventilation, and Air Conditioning (HVAC) systems, materials, and operation schedules, were collected (Neale et al. 2022). More details on the heat stress assessment, workplace productivity, reference building, and climate data are discussed below.

2.1 Heat stress assessment

International Organization for Standardization (ISO) 7243 – Ergonomics of the thermal environment (ISO 2017) recommends wet-bulb globe temperature (WBGT) as an indicator for heat stress assessments (d'Ambrosio Alfano et al. 2014). Hourly WBGT values are calculated using the energy performance simulation data from the reference net zero-carbon office building. The indoor WBGT (°C) is calculated in Equation (1) as given in Lemke and Kjellstrom (2012).

$$\mathrm{WBGT} = 0.67 \times T_{\mathrm{W}} + 0.37 \times T_{\mathrm{a}} \tag{1}$$

where T_{W} is the wet-bulb temperature (°C), T_{a} is the dry-bulb temperature (°C). T_{W} (°C) is estimated using hourly dry-bulb temperature T_{a} (°C) and hourly relative humidity [RH%] (%) using Equation (2) from Stull (2011).

$$\begin{aligned} T_{\mathrm{W}} = {} & T_{\mathrm{a}} \times \arctan\left(0.151977 \times (\mathrm{RH\%} + 8.313659)^{\frac{1}{2}}\right) \\ & + \arctan(T_{\mathrm{a}} + \mathrm{RH\%}) - \arctan(\mathrm{RH\%} - 1.676331) \\ & + 0.00391838 \times (\mathrm{RH\%})^{\frac{3}{2}} \times \arctan(0.023101 \times \mathrm{RH\%}) \\ & - 4.686035 \end{aligned} \tag{2}$$

2.2 Workplace productivity

Heat stress induced decline in workplace productivity can be assessed using a variety of formulations, as mentioned in Kong and Huber (2022) and briefly described in Dunne et al. (2013), Bröde et al. (2018), Kjellstrom et al. (2018), Foster et al. (2021), Foster et al. (2022). The evaluation of the relative merits of these methodologies is beyond the study scope. Therefore, to assess workplace productivity in the reference building, the method from Dunne et al. (2013) and implemented by Gosling et al. (2018) is used in this study. This method from Dunne et al. (2013) follows the National Institute for Occupational Safety and Health (NIOSH) standards (Gosling et al. 2018). The workplace productivity decline is calculated using Equation (3) as in Dunne et al. (2013). When WBGT is below 25 °C, there is no workplace productivity decline; when WBGT is above 33 °C, there is a 100% workplace productivity decline (%) according to Dunne et al. (2013).

$$\begin{aligned} & \text{Workplace productivity decline} \\ & = 100 - \left[100 - \left(25 \times \max\left(0, \mathrm{WBGT} - 25\right)^{\frac{2}{3}}\right)\right] \end{aligned} \tag{3}$$

WBGT is widely regarded as heat stress indicator for strenuous work conditions. However, the thresholds from Equation (3) combine light, moderate, and heavy work into one single metric. This is done through the observation of light work as 50% of moderate work, and moderate work as 50% of heavy work (Dunne et al. 2013). The three different levels of work are then plotted into a single graph and extrapolated with a value of 25 °C and 33 °C as safe and at risk thresholds for work making the methodology from Equation (3) suitable for office environments.

2.3 Reference net zero-carbon timber building

The reference net zero-carbon timber building is in Westerlo (51.09° N, 4.91° E), 52 km from Brussels, Belgium, in mixed humid climates as per the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) 169 – Climatic data for building design standards (ANSI/ASHRAE 2020). The building incorporates circularity principles and is carbon-neutral, catalyzing modular constructions. The reference building is constructed using circular materials that are renewable, reusable, upcycled or recycled and can be used for long durations (Claeys 2022). The building is a timber construction with a framework made of CLT components (Binderholz GmbH n.d.) featuring a modular office design with adaptable workspaces. The building is designed to be completely disassembled when it becomes outdated (Al-Obaidy et al. 2022). For this purpose, the connection depends on dry fastening techniques. The interior partitions, floors, and ceiling are all made of timber, and the floor tiles and partitions are attached with dry adhesive. According to (ResourceFull n.d.), 22,500 kg of secondary raw materials were used to construct the building foundation, saving 13,000 kg of CO_2 emissions compared to regular foundations. The building exterior view (Beneens 2022) and the simulation model (Claeys and Attia 2022) as in Figure 1.

The building has a total surface area of 2400 m^2 and a window-to-wall ratio of approximately 30.5%. The building properties and occupant profiles were characterized (www.energiesparen.be/epb-pedia/epb-eisen). The energy performance assumptions like insulation, installations, ventilation, and overheating follow the Flemish energy performance regulations for 2019 (Al-Obaidy et al. 2022). This building has three glazed facades and is all-electric. Vacuum glass glazing is used for the ground floor, and triple glazing is used for the upper floors. The building also has a mechanical ventilation system at a rate of 7.55 L/(s·person) with heat recovery. To meet the space heating and cooling demand, six boreholes are connected to a ground source water to water heat pump. The reference building has an occupancy rate of 17.25 m^2/person and an internal equipment gain of 6 W/m^2. More details on the building, including the floor plans, are available in Al-Obaidy et al. (2022) and Claeys (2022). The energy performance simulation model is available in open access (Claeys and Attia 2022). The model calibration used the energy consumption values given in the EPB report (Claeys 2022) to estimate the normalized mean bias error (NMBE) value according to ASHRAE Guideline 14 (ANSI/ASHRAE 2014). The model calibration indicated an NMBE of −0.4%. The building envelope characteristics of the baseline configuration, including the thermal transmittance values, are listed in Table 1.

Occupancy profiles for the reference net zero-carbon timber building are obtained from (D'Oca and Hong 2015), derived from ASHRAE 90.1 – Energy standard for buildings except low-rise residential buildings (ANSI/ASHRAE 2014). The maximum occupancy in the reference building is estimated from 09h00 to 17h00, with around 90% occupancy during work hours. With the increasing level of thermal mass in each configuration, the occupancy rate is increased to 11.50 m^2/person and 5.75 m^2/person, and internal equipment gain is increased to 12 W/m^2 and 18 W/m^2 for Strategy 01 and Strategy 02 to create a more exacerbated indoor built

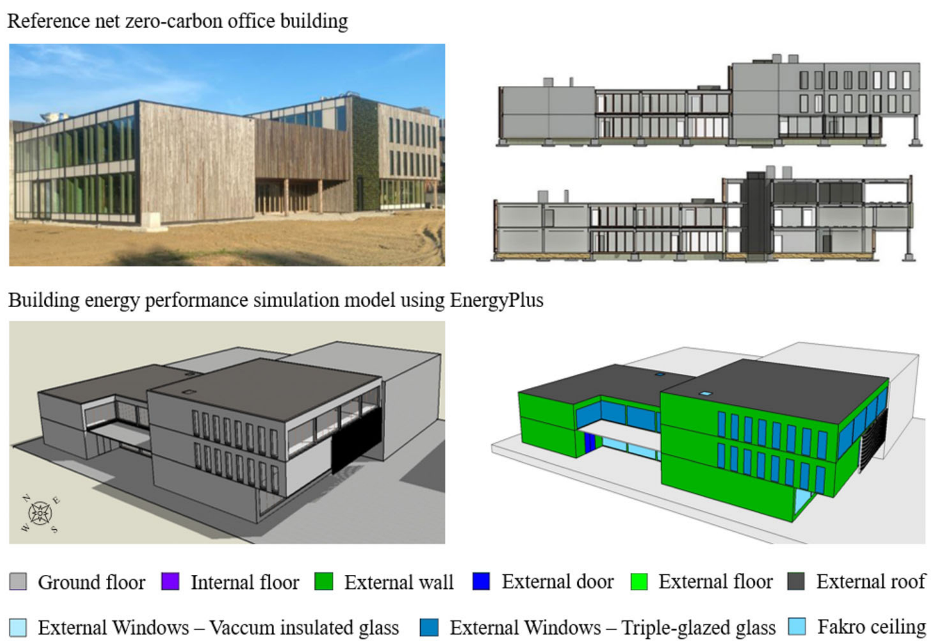

Fig. 1 Illustration of the reference net zero-carbon timber building view (Beneens 2022) and energy performance simulation model (Claeys and Attia 2022)

Table 1 Envelope characteristics of the reference net zero-carbon timber building

Envelope	Layers	Materials used	Thickness (m)	*U*-value (W/(m^2·K))
Ground floor	Outer	Shells ground	0.0100	0.138
	Third	Lime and hemp	0.0100	
	Second	Lime screed	0.0100	
	Inner	Floor cover	0.0100	
External floor	Outer	Watertight layer	0.0050	0.219
	Fifth	Standard insulation	0.0800	
	Fourth	CLT softwood	0.0160	
	Third	Wood fibre board	0.0500	
	Second	Oriented strand board	0.0180	
	Inner	Floor cover	0.0200	
Internal floor	Outer	CLT softwood	0.2000	0.719
	Inner	Floor cover	0.0200	
External roof	Outer	Bitumen	0.0030	0.226
	Fourth	Oriented strand board	0.0180	
	Third	Standard insulation 2	0.1400	
	Second	Shells roof	0.0800	
	Inner	CLT softwood	0.1000	
External wall	Outer	Watertight layer	0.0050	0.170
	Fourth	Wood fibre board	0.0400	
	Third	Wood framing (15)/cellulose (85)	0.2350	
	Second	Gypsum plasterboard	0.0130	
	Inner	Vapor tight layer	0.0010	
Internal partition	Outer	Gypsum plasterboard	0.0250	1.639
	Second	Air gap	0.1000	
	Inner	Gypsum plasterboard	0.0250	
Doors	External	Metal surface	0.0020	3.820
		Glass fibre board	0.0033	
		Metal surface	0.0020	
Doors	Internal	Painted Oak	0.0350	2.823

environment. The schematic view of modeled walls and internal floors for various building configurations is shown in Figure 2.

The weather files used for the study are created using the regional climate model, Modele Atmospherique Regional (MAR) v3.11.4 (Kittel 2021). Extreme meteorological year (XMY) weather files for Shared Socioeconomic Pathway (SSP) 5 that outline significant hurdles to climate change mitigation are used for simulations to assess building performance during worst-case scenarios. To create the XMY files, the most extreme or outlier months from a given data set are selected rather than regular months, as in typical meteorological years (TMY) (Ferrari and Lee 2008). Even though there are various approaches to creating these weather files, these are developed based on ISO 15927-4 – Hygrothermal performance of buildings (ISO 2005) and this method is described in Doutreloup et al. (2022). Elements software is used to convert the weather files in comma-separated csv format to epw format for building simulation analysis using Elements software (Bigladder Software 2016). The 2030s_Current represents XMY file for period 2020 to 2040 representing existing situation. 2050s_Midfuture scenario and 2090_Future scenario represent XMY file for periods 2040 to 2060 and 2080 to 2100, respectively. The midfuture and future scenarios were selected according to existing climate change impact studies like (Rahif et al. 2022). The assessment of hourly outdoor dry-bulb temperature (°C) for different weather scenarios is shown in Figure 3. The average, maximum, 3rd quartile, median, 1st quartile, and minimum values for the hourly outdoor dry-bulb temperature (°C) are listed in Table 2. All of the weather data used in the study is available in open source (Doutreloup and Fettweis 2021).

The boundary conditions for the study are as follows:

a. The study focuses on impact of heat on workplace productivity loss towards the end of the century due to climate change.
b. Regarding climate files, EMY files, derived from MAR v3.11.4 in Brussels, Belgium, are used.
c. A net zero-carbon timber building in Westerlo, Belgium, is used as the reference building.
d. Internal thermal mass is used as the primary study variable with changes to combinations of construction materials used for internal walls and floors.
e. Heat stress and workplace productivity are primary study outputs calculated for different configurations with varying thermal mass.

3 Results

Hourly indoor WBGT (°C) values were calculated for various weather scenarios towards the end of the century, including 2030s_Current, 2050s_Midfuture, and 2090s_Future scenarios for the building configurations with low, medium, and high thermal mass. The hourly WBGT (°C) values in the reference net zero-carbon timber building from May to September are shown in Figure 4. Since the case study was based on an office building, the WBGT values were calculated between 09h00 and 17h00 based on the workplace occupancy schedule from D'Oca and Hong (2015). On the warmest days, the hourly indoor WBGT values of the Baseline with low thermal mass reached a maximum value up to 29.7 °C for 2030s_Current, 29.9 °C for 2050s_Midfuture, and 32.3 °C for 2090s_Future. For Strategy 02 with medium thermal mass, the maximum WBGT values varied from 26.2 °C for 2030s_Current, 26.7 °C for 2050s_Midfuture, and 29.3 °C for 2090s_Future. Strategy 03 with high thermal mass, gave the best performance

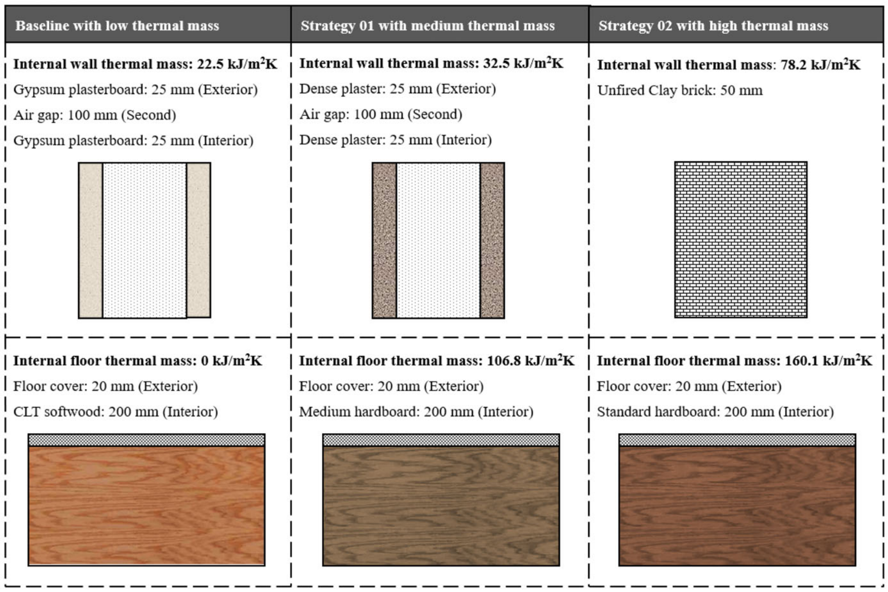

Fig. 2 Illustration of the reference net zero-carbon timber building view and simulation model

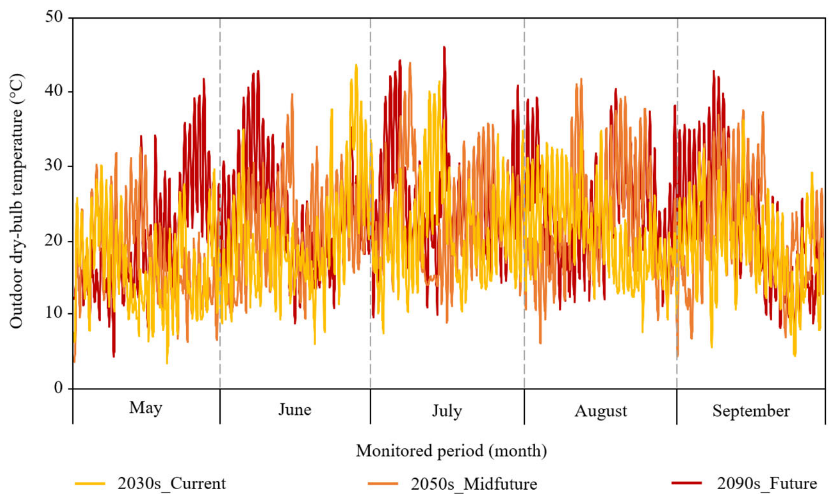

Fig. 3 Variations in hourly outdoor dry-bulb temperature (°C) from May to September for different weather scenarios towards the end of the century

Table 2 Statistical parameters for weather scenarios used for energy performance simulations

Scenario	Hourly outdoor dry-bulb temperature (°C) from May to September					
	Average	Maximum	3rd quartile	Median	1st quartile	Minimum
2030s_Current	19.7	43.6	23.7	18.8	14.9	3.4
2050s_Midfuture	21.1	43.9	26.0	19.9	15.6	3.6
2090s_Future	22.3	46.1	27.8	22.2	17.1	4.3

compared to Baseline and Strategy 01, with maximum WBGT values of 26.0 °C for 2030s_Current, 26.6 °C for 2050s_Midfuture, and 28.4 °C for 2090s_Future during the warmest days. The maximum WBGT value for Strategy 02 towards the end of the century was 3.9 °C lower than the Baseline configuration. The worst variations in hourly WBGT values were observed during July and August. However, towards the end of the century, worsening WBGT values were observed for May and September.

The hourly indoor WBGT value variations are shown in Figure 5. Although the estimated maximum and minimum WBGT values vary between different configurations and

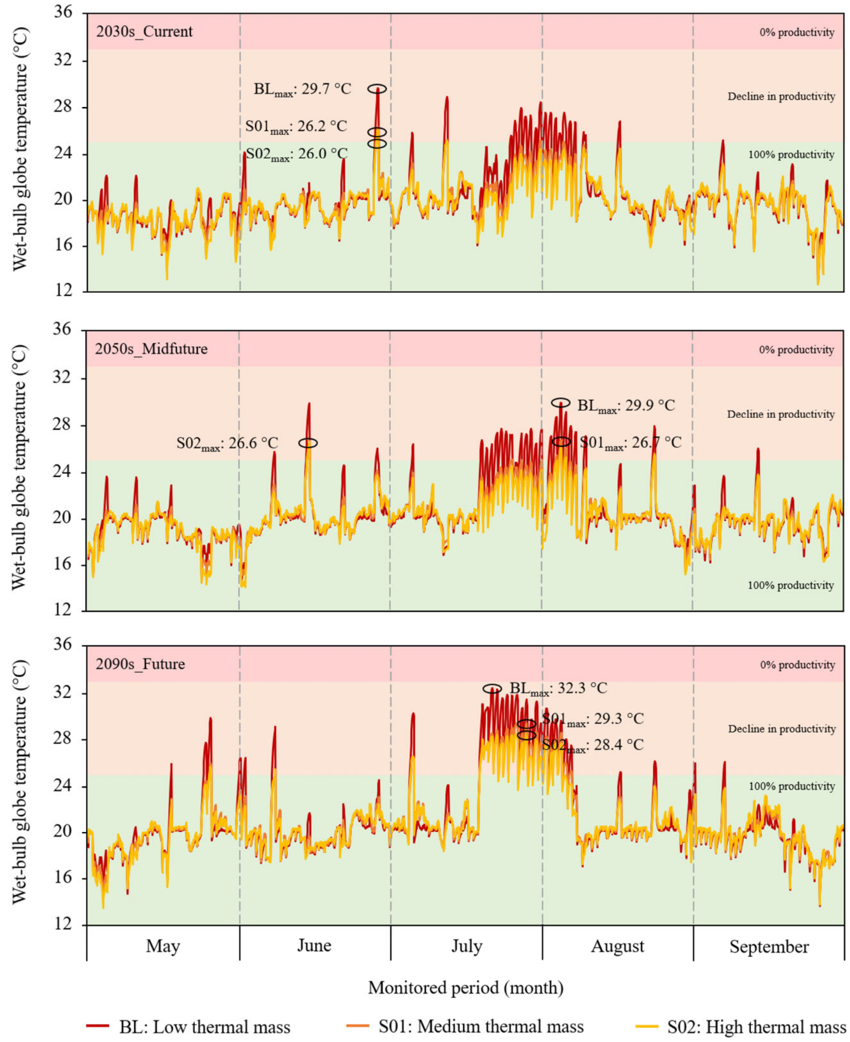

Fig. 4 Hourly wet-bulb globe temperature (°C) in the reference net zero-carbon timber building for different weather scenarios from May to September towards the end of the century

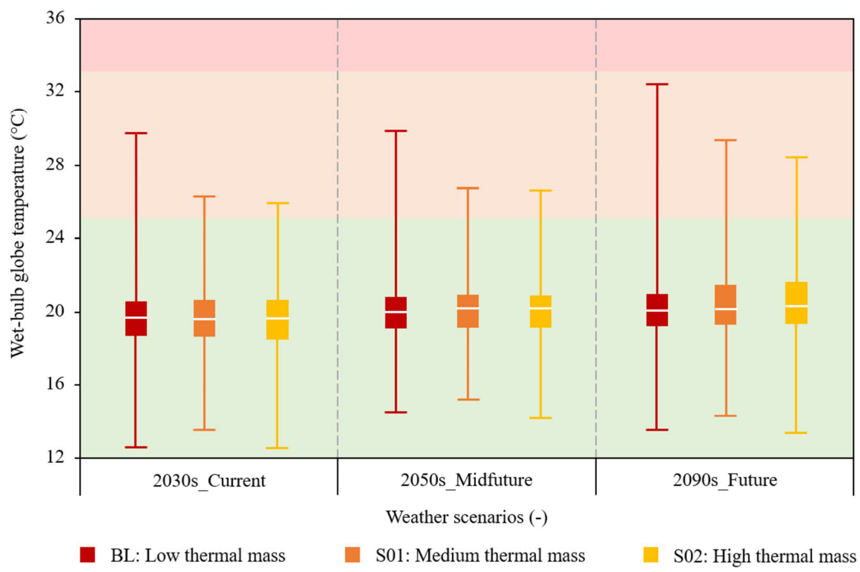

Fig. 5 Hourly wet-bulb globe temperature (°C) in the reference net zero-carbon timber building for different weather scenarios from May to September towards the end of the century

weather scenarios, the median value across all simulations is consistently within 20 °C ± 0.5 °C for all the building configurations under high warming scenarios towards the end of the century. The largest variation in maximum and minimum WBGT values are observed consistently for the Baseline with low thermal mass. The largest WBGT variation is recorded for the 2090s future scenario with a difference of 18.9 °C. This variation was 17.1 °C for 2030s_Current and 15.4 °C for 2050s_Midfuture. The largest WBGT variation for Strategy 01 and Strategy 02 was also observed towards the end of the century for the 2090s_Future with a value of 15.2 °C and 15.1 °C. Additionally, variation between maximum and minimum WBGT values for Strategy 01 and Strategy 02 for 2030s_Current with 12.7 °C and 13.4 °C and 2050s_Midfuture with 11.6 °C and 12.5 °C was observed.

The decline in workplace productivity (%) in the reference net zero-carbon timber building for different weather scenarios from May to September towards the end of the century is shown in Figure 6. By the end of the century for 2090s_Future, the hourly indoor workplace productivity decline could go up to 94.8% for Baseline with low thermal mass, 66.5% for Strategy 01 with medium thermal mass, and 56.6% for Strategy 03 with high thermal mass for the worst-case scenario under high warming scenarios. This workplace productivity decline is 25% and 22.6% higher for Baseline, 37.8% and 31% higher for Strategy 01, and 32.3% and 22.9% higher for Strategy 02 compared to 2030s_Current and 2050s_Midfuture. This decline in workplace productivity is more evident for the Baseline of reference net zero-carbon timber building with low internal thermal mass for all the weather scenarios. The worst decline in workplace productivity was observed during July and August across all weather files. However,

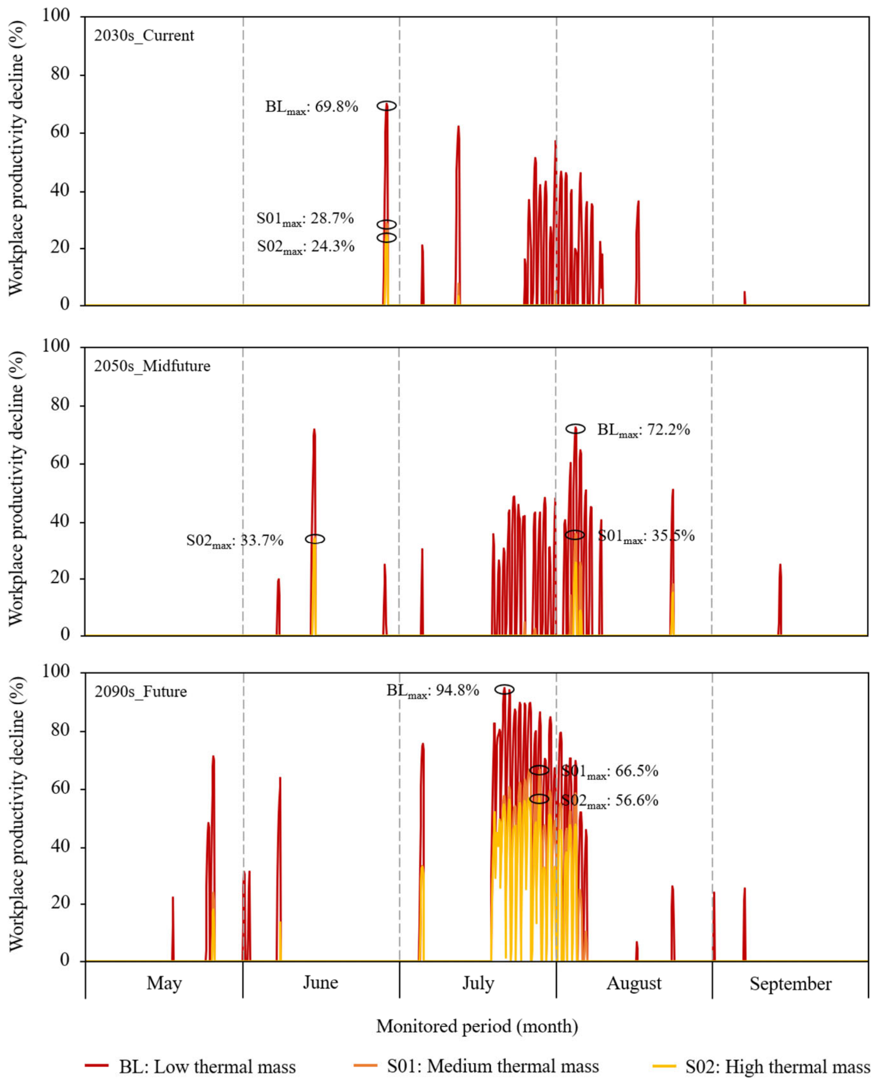

Fig. 6 Hourly workplace productivity loss (%) in the reference net zero-carbon timber building for different weather scenarios from May to September towards the end of the century

by the end of the century, shoulder months like May and September also showed a considerable decline in workplace productivity.

The average workplace productivity decline (%) due to climate change induced heat stress on reference building for different configurations and weather scenarios is shown in Figure 7. As in previous cases, the Baseline with low thermal mass gave the highest average workplace productivity decline with 2.3% for 2030s_Current, 3.3% 2030s_Midfuture, and 8.2% for 2090s_Future, which is 3.5 and 2.5 times higher than the current and midfuture scenarios. There is no considerable difference in average workplace productivity decline for Strategy 01 with medium thermal mass and Strategy 02 with high thermal mass for 2030s_Current and 2050s_Midfuture scenarios. This indicates that increasing thermal mass beyond Strategy 01 will not considerably improve workplace productivity for the current and midfuture scenarios. However, there is a more substantial difference towards the end of the century for 2090s_Future. Therefore, Strategy 02, with high thermal mass, is a more appropriate measure for heat stress mitigation for future scenarios. In addition, the future scenario also calls for additional mitigation and adaptable measures for ideal indoor workplace productivity.

4 Discussions

Climate projections from the study indicate an increase in warmer climates towards the end of the century. These considerations, though well known, are reinforced by the study results. The warmer climates will lead to heat exposure and productivity losses in the reference net zero-carbon timber building. The impact of climate change induced heat stress and building design parameters like thermal mass on workplace productivity is relatively overlooked, and this study attempted to investigate the relationship between these variables.

4.1 Main findings

The study indicates that the Baseline with low thermal mass decreases workplace productivity by 2.3% for the 2030s_Current weather scenario. Furthermore, climate change induced heat stress will increase the decline in workplace productivity for the Baseline towards the end of the century for 2090s_Future by 3.6 times up to 8.2% due to increased WBGT values caused by high warming conditions. The ability of Strategy 02 with high thermal mass to store heat in walls and floors compared to the Baseline with low thermal mass offsets the impact of warm days on WBGT levels. The substantial impact of climate change induced heat stress on indoor workplace productivity in net zero-carbon timber buildings can be avoided by increasing the internal thermal mass. The study observed the lowest average productivity decline for Strategy 02 with high thermal mass with 0.1% for 2030s_Current, 0.3% for 2050s_Midfuture, and 3.9% for 2090s_Future scenarios. Additionally, there is minimal difference in workplace productivity loss between Strategy 01 with medium thermal mass and Strategy 02 with high thermal mass in 2030s_Current and 2050s_Midfuture. However, this difference increases to a value of 1% towards the 2090s_Future since the impact of temperature increase in the 2090s_Future is more efficiently offset by higher thermal mass of Strategy 02 in comparison to Strategy 01 with medium thermal mass as shown in Figure 7.

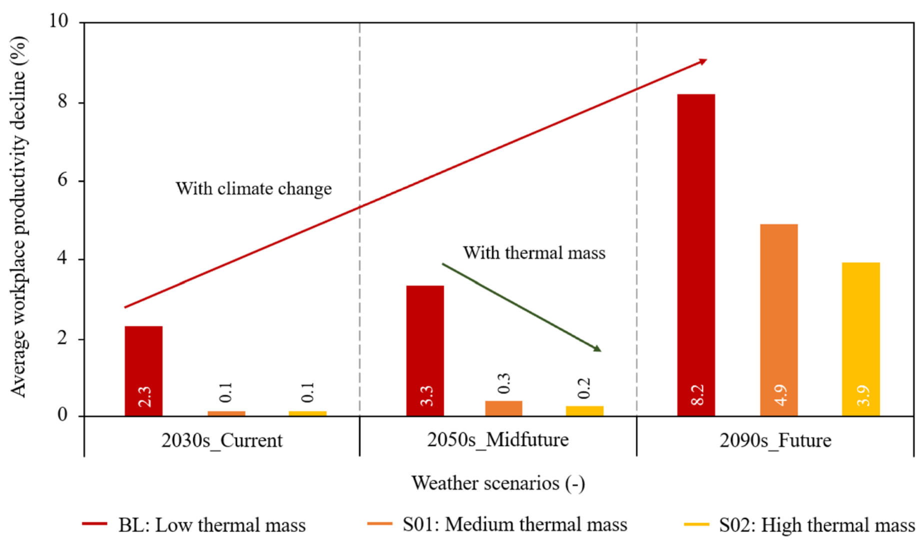

Fig. 7 Average workplace productivity decline (%) in the reference net zero-carbon timber building for different weather scenarios from May to September towards the end of the century

Among the configurations tested in the study, Strategy 02 with high thermal mass ensured the lowest indoor WBGT values and the greatest benefits to workplace productivity even with higher occupancy rate and internal equipment gains. However, when comparing Strategy 01 with medium thermal mass and Strategy 02 with high thermal mass in the current and mid-future scenarios, it was observed that there was no significant variation in workplace productivity decline, as in Figure 7. This shows that increasing thermal mass beyond Strategy 01 will not improve workplace productivity significantly in current and midfuture scenarios. Nevertheless, there was a difference in workplace productivity decline near the end of the century, and as a result, for future scenarios, Strategy 02 with high thermal mass, is a more desirable measure for heat stress mitigation. Therefore, a higher percentage of workplace productivity can be obtained by increasing the thermal mass of the reference timber building until the end of the century.

4.2 Design recommendations

The variations in outdoor temperature will impact indoor temperature in timber buildings, and increasing internal thermal mass will reduce the WBGT variations in the built environment (Slee and Hyde 2015). The baseline design of reference net zero-carbon timber building has a low thermal mass. Therefore, the study recommends increasing the internal thermal mass of timber dwellings through materials used for internal walls and floors to minimize variations in WBGT values and the heat stress impact on workplace productivity. Materials like dense plaster, unfired clay bricks, etc., for internal walls and hardboard panels for internal floors can effectively increase thermal mass in the building while adhering to its circularity principles. However, it is worth noting that increasing thermal mass beyond the necessary levels does not benefit workplace productivity in the reference building, as shown in Figure 7 for 2030s_Current and 2050s_Midfuture scenarios. This indicates that if there is more thermal mass capacity than the required level, the excess capacity will not be used and will not affect the indoor environment. Overall, as shown in Figure 7, there is a significant loss of workplace productivity between 2050s_Midfuture and 2090s_Future scenarios. This indicate that thermal mass, although effective, should be combined with more retrofit strategies like solar shading, cool roof, among others. It is also essential to address workplace productivity for different building orientations and floors as this will allow designers to create better workplaces in the future. Finally, to improve the accuracy of the early-stage building design process, building modelers and engineers should also use intermediate periods like weather data for the 2070s and include adaptation measures, including occupant behavior.

4.3 Strengths and limitations

The main strength of this study is its comparative approach, which combined climate change scenarios towards the end of the century and various internal thermal mass levels to assess their impact on workplace productivity. The reference net zero-carbon timber building is Belgium's first fully circular office building that is demountable, waste-free, CO_2 neutral, cement-free, and with a recyclable screed to catalyze modular constructions (Al-Obaidy et al. 2022). Furthermore, the findings add to the existing knowledge base on the effectiveness of thermal mass as a passive strategy for improving workspace productivity in timber office buildings. The high spatial resolution climate data of around 5 km, based on the Regional atmospheric model (MAR) adds to the strengths of this study as described in (Amaripadath et al. 2023). The limitation of this study is that although the paper offers insights into the efficacy of different internal thermal mass configurations, this is a case study on a net zero-carbon timber building near Brussels. Therefore, future studies must compare these results with similar studies from mixed humid climate zones.

4.4 Implications for practice and research

The replacement of steel and concrete by timber in construction industries on a large scale has the potential to substantially decrease emissions while improving carbon storage in cities, both of which are essential for climate change mitigation according to Oliver et al. (2014), Churkina et al. (2020), and Churkina and Organschi (2022). Current building codes in Europe do not mandate regulations for indoor workplace productivity loss brought on by climate change in timber office buildings. The study findings can thus contribute to the future Energy Performance of Buildings Directive (EPBD) policy recommendations and revisions regarding workplace productivity in a changing climate. The study results will also promote the design of new timber buildings with the potential to withstand climate change induced heat stress using low-energy and low-carbon measures. A significant opportunity exists in the timber construction industry, and ensuring an ideal indoor built environment will be an important aspect of this development. Our study revealed the impact of climate change induced heat stress will have significant negative effects on workplace productivity in timber office buildings.

The relationship between climate change, building thermal mass, and indoor workplace productivity will help policymakers make better decisions about improving the indoor built environment in timber buildings. Efforts must also be made to improve workplaces' ability to adapt to rising temperatures. Adaptation measures that are planned, autonomous, or a combination of both (Parsons et al. 2021), alongside mitigation strategies like building thermal mass, can potentially lessen these impacts. Although government organizations play an important role in creating a regulatory framework to implement effective mitigation and adaptation measures, the role of employers and building operators is also crucial in facilitating behavioral changes (Kjellstrom et al. 2019). With the emergence of carbon neutrality strategies in building sectors like timber constructions, it is still uncertain how the economic benefits of these strategies would compare to the workplace productivity loss due to heat stress. Comparison studies involving different building types and operations are critical for assessing the benefits of these carbon-neutral strategies (Zhao et al. 2022).

5 Conclusions

Climate change can impact building performance in several ways, but hotter summer temperatures are of particular concern for indoor workplace productivity. Frameworks like the European Green Deal aim to change the EU into an advanced, sustainable, and competitive economy while ensuring that there are no net emissions of greenhouse gases by 2050 (European Council 2022). Additionally, the circular economy action plans from the EU prioritize constructing timber buildings with a capacity for long-term carbon storage (European Commission 2019). To facilitate the establishment of these climate-neutral frameworks and the implementation of new timber constructions, assessing how these new developments will impact indoor workplace productivity is important. This study focused on a timber office building to conduct an up-to-date investigation into how these buildings will perform in a changing climate and how workplace productivity will be affected in this scenario. From assessing the wet-bulb globe temperature levels for different configurations and weather scenarios, high thermal mass is desirable for timber buildings and structures to lessen the effects of heat exposure in the built environment. Baseline with low thermal mass recorded a maximum WBGT value of 29.7 °C, 29.9 °C, and 32.3 °C, in addition to maximum hourly productivity losses up to 69.8%, 72.2%, and 94.8% for current, midfuture, and future scenarios. Whereas Strategy 01 with medium thermal mass indicated WBGT values of 26.2 °C, 26.7 °C, and 29.3 °C, and productivity losses up to 28.7%, 35.5%, and 66.5%, and Strategy 02 with high thermal mass showed WBGT values of 26 °C, 26.6 °C, and 28.4 °C, and work productivity loss of 24.3%, 33.7%, and 56.6%.

The maximum and minimum WBGT variations were also higher in Baseline with low thermal mass configuration compared to Strategy 01 with medium thermal mass and Strategy 02 with high thermal mass. One of the main takeaways from the study is that workplace productivity will continue to decline in timber office buildings with low thermal mass unless effective mitigation strategies are adopted. Additionally, increasing thermal mass beyond the medium level does not provide any additional benefits to workplace productivity for current and midfuture scenarios. However, the potential benefits with high thermal mass can be observed towards the end of the century in future weather scenarios. Future research should enhance the indoor built environment in timber buildings by assessing the capability of adaptation measures like behavioral changes, mitigation measures like improved thermal mass against heat exposure, and decline in workplace productivity due to climate change. Although the study findings presented here support previous research findings on climate change similar to Peters et al. (2013) and Hansen et al. (2000) and its negative impacts on building performance (Amaripadath et al. 2023), it adds to existing knowledge by providing evidence-based results on the impacts of heat exposure on workplace productivity in timber office buildings towards the end of the century. In addition, the study provides practical solutions to rectify this decline in workplace productivity while adhering to the core building principle of net-zero carbon emissions by minimizing the negative environmental impacts of the building material. The study primarily focuses on impact of heat on workplace productivity. However, future research should integrate other physiological, psychological, and social factors that might impact productivity in addition to effects of climate change induced heat.

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article. Mattheos Santamouris is an Editorial Board member of *Building Simulation*.

Author contribution statement

Deepak Amaripadath: conceptualization, methodology, formal analysis, software, data curation, visualization, writing—original, writing—reviewing and editing. Mattheos Santamouris: conceptualization, methodology, validation, writing—reviewing and editing. Shady Attia: conceptualization, methodology, supervision, validation, writing—reviewing and editing

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