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On the Influence of Thermal Mass and Natural Ventilation on Overheating Risk in Offices

Arianna Brambilla [1,2,*], Jerome Bonvin [3], Flourentzos Flourentzou [3] and Thomas Jusselme [2]

1 School of Architecture, Design and Planning, University of Sydney AU, Camperdown, NSW 2006, Australia
2 Building 2050 Research Group, Ecole Polytechnique Fédérale de Lausanne (EPFL), 1700 Fribourg, Switzerland; thomas.jusselme@epfl.ch
3 ESTIA SA Lausanne, EPFL Innovation Park, 1015 Lausanne, Switzerland; bonvin@estia.ch (J.B.); flourentzou@estia.ch (F.F.)
* Correspondence: arianna.brambilla@sydney.edu.au

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Abstract: Free cooling strategies are gaining importance in design practice due to the increased risk of overheating in well-insulated buildings with high internal loads such as offices. The state of the art highlights that the most efficient passive solution for indoor temperature stabilization and control is the integration of thermal mass with an optimized ventilative cooling profile to enhance the thermal cycle of heat storage. Due to its cyclical behavior, thermal mass effects are difficult to predict and quantify with the traditional steady-state approach to building thermal performance. Dynamic thermal simulations help to assess a building's behavior under transient situations, including the thermal mass influence. However, building codes usually include thermal simulations based on standard assumptions: typical meteorological year (TMY), standard occupancy, standard daily-based lighting and appliances profiles, and standard weekly-based occupancy. Thus, when assumptions change, the actual behavior of the building may vary consistently from the predicted conditions. In this paper, we focused on the ability of thermal mass to contrast the influence of variations from the standard assumptions, especially in relation to climate and ventilation profiles. The results show the necessity of encompassing different risk scenarios when evaluating a free cooling solution performance. Among the different scenarios simulated, natural ventilation misuse shows greater influence on the thermal indoor environment, especially if coupled with low thermal mass.

Keywords: thermal inertia; thermal mass; natural ventilation; passive cooling; energy efficiency; overheating; thermal simulations; future proofing; climate change mitigation

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1. Introduction

Globally, buildings consume 20% of the energy delivered each year and their energy demand increase by 1.5% yearly [1]. The greatest part of this energy is used by the mechanical cooling, heating, and ventilation systems (HVAC) to regulate the indoor temperature and provide a pleasant thermal environment [2], ranked as the primary aspect of occupants' satisfaction and most influencing factor in determining the total energy demand of a building [3]. Thermal satisfaction in offices is mainly linked to cooling and it is directly linked to the increasing cooling energy demand in the commercial sector [4], due to the increased temperature, increased insulation requirements, and increased appliance heat gains [5]. The European Directive on the Energy Performance of Buildings sets ambitious goals to reduce this request toward the concept of Nearly Zero Energy Building [6]. However, the attention given to thermal insulations as a mean to reduce the heating needs [7] led to the paradoxical situation where lightweight and over-insulated constructions cannot dissipate the heat, presenting a higher overheating risk even in continental cold climates, such as Switzerland [8].

Traditionally, heavy constructions succeeded in stabilizing indoor temperatures and reducing the cooling energy demand [8–15]. The thermal mass provided by bricks [16,17], concrete [18] and stones [19] is able to store and release heat from the surroundings, consequently changing the indoor temperatures [20]. The state of the art underlines the contribution of these massive materials in shifting the indoor heat peaks. This property is quantified through the decrement factor [21,22]. Matching the building's typology to the right decrement factor is highly critical during the design phase [23], as it sets the building thermal performance and the ability to synchronize the thermal mass cycle and the building occupancy schedule [24].

To enhance its effect and allow quick discharge cycles, thermal mass should be coupled with an adequate ventilation strategy, which can extract the heat stored in the building and prepare the mass for another thermal cycle [25–27]. However, the potential of the passive design is usually quantified according to national normative and efficiency standards, which rely on a series of assumption of average and common conditions of climate and building usage, in terms of appliances, lighting, and occupancy [28]. The result of this approach is the application of a series of schedules for each of the component assumed [29,30]. Previous studies highlighted that thermal mass benefits are more visible in critical situations when the thermal inertia is capable of stabilizing indoor temperatures [12]. Moreover, the increased global temperature brings about the question of how to provide buildings able to adapt to warmer summers in the future [5,31]. The ability of buildings to respond to critical situations should be tested to assure resilience to changes from the standard design assumptions. This paper aims at the clear definition of the benefits of thermal inertia and ventilative cooling in preventing overheating due to unpredictable critical events. The goal is to understand the role of these two passive design strategies in relation to several risk scenarios, where the building is exposed to critical conditions. The analysis is assessed in the framework of the smart living lab building [32–34], aimed at the design of a future efficient low-carbon building.

The objective of the study is to analyze the overheating hours associated with different scenarios applied to the specific case of an office building located in Fribourg (CH). The architectural scenarios used differ from the thermal mass level and the ventilation strategy applied; moreover, a series of risk scenarios are used to investigate the effects of design uncertainties on the final thermal performance of the architectural scenarios.

2. Methods

2.1. Building Model

The model used for the simulations consists in a double-office room, designed according to the Swiss standard practice [30]: it has an internal surface of 18 m^2, minimum height of 3 m, two windows on opposite façades, oriented on the SW/NE axis. The particular design was inspired also by a facility test in Fribourg, used for the calibration of the virtual model, as described in previous works [32,34]. The architectural plan is shown in Figure 1.

In the simulations, the heat gains profile was the combination of standard occupational, lighting, electrical profiles and solar radiation taken from SIA 2024 [29]. The shading system has been considered as optimally designed, able to block all the direct radiation during summer and enhance passive heating during winter. This model is not representative of a real situation, as even a perfectly designed shading system allows for solar radiation, especially in the first part of the day, when temperatures and irradiation are not at their daily peak and, therefore, they do not represent a criticism for the thermal indoor environment. However, due to the highly variability of the solar gains during the validation process, the model used considers an amount of solar radiation entering the room that is standardized according to the building code [29]. In this way, the model acknowledges an average value of solar gains without introducing the daily variability.

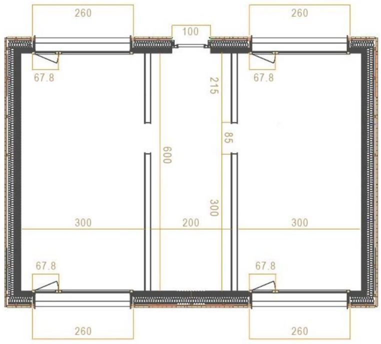


Figure 1. Architectural section of the modular standard double-office used for the simulations [32].

2.2. Simulation Scenarios

The geometry has been used to create the simulation models, combining six thermal mass levels (scenarios TI) with five different ventilation strategies (scenarios V). Moreover, four additional risk scenarios (scenarios R) have been used to evaluate the criticisms related to the ventilation strategies used as natural cooling. DIAL+ [35] has been used to perform the dynamic thermal simulations. DIAL+ is a software developed by ESTIA SA and validated according to the European norms [36–38]. From the combination of the different scenarios, we created a matrix of simulations, containing all the possible combination TI + V. The virtual building model has been assessed accordingly.

2.2.1. Thermal Mass Levels

Thermal mass has been varied to create six different TI levels: from very lightweight (TI1), as the typical new energy-efficient Swiss construction typology, to very heavy (TI6). The classification and calculation of the TI levels followed the specific Swiss norm on thermal properties of building elements [30]. The desired mass level is quantified by the total heat capacity of the room, depending on the different materials used in the envelope and the thermal properties of the surfaces that delimit the room, as per (1).

$$C_m = \sum A_i \cdot x_i \tag{1}$$

where A_i is the floor area of ith-wall of the zone expressed in m^2 and x_i is the heat capacity of the ith-wall.

Table 1 shows the construction technology of the base case. Scenario TI1 is used as reference case for TI and it is modeled as very lightweight construction, reflecting the timber-based envelope frequently used for the new energy efficient buildings in Switzerland. The construction technology of TI1 is based on the typical cross-laminated timber structure (CLT technology).

Table 1. Construction technology of TI1, used as reference case.

Walls	Roof	Floor
Indoor air	Indoor air	Indoor air
CLT structure 140 cm	Wooden panels 2.5 cm	Linoleum
Vapor barrier	Vapor barrier	Acoustic insulation 0.9 cm
Polyurethane insulation 180 cm	Polyurethane insulation 180 cm	Wooden panels 2.5 cm
Waterproofing	Bitumen elastomeric membrane	Polyurethane insulation 35 cm
Ventilated cladding	Outdoor air	CLT structure 140 cm
Outdoor air	-	Outdoor

The other scenarios are built from TI1, adding toward the interior the materials indicated in the table. In TI2 the walls are rendered with a synthetic mixture that changes the internal surface properties; TI3 and TI5 have an additional concrete screed in the floor; while TI4 and TI5 have compressed earth bricks in direct contact with the indoor air (CEB) as additional wall layer. In scenario TI6, the CLT is completely substitute by a concrete wall with the same bearing capacity. Table 2 shows the different scenarios, the envelope materials and the final heat capacity of the room.

Table 2. Thermal mass scenarios used for the analysis. Calculation followed SIA380/1, based on the heat capacity of the room that depends from the thermal properties of each surface that delimits the considered room.

Scenario	Longitudinal Walls	Short Walls	Roof	Floor	C (Wh/m^{2}K)
TI1	Light-wooden	Light-wooden	Light-wooden	Light-wooden	39.1
TI2	TI1 + synthetic rendering	TI1 + synthetic rendering	TI1	TI1	46.2
TI3	TI1	TI1	TI1	TI1 + cement screed	50.4
TI4	TI1 + CEB	TI1	TI1	TI1	58.7
TI5	TI1 + CEB	TI1	TI1	TI1 + cement screed	70
TI6	Concrete + mortar rendering	Concrete + mortar rendering	Concrete + mortar rendering	Concrete + cement screed	94.4

2.2.2. Ventilation Profiles

Ventilation is essential for cooling and hygienic purposes, as it change the indoor air, maintaining air quality high. In the analysis, different types and strategies of ventilation have been tested in relation to the smart living building framework [33].

V1, considered as reference case, only includes the minimum requested rate of hygienic ventilation during occupancy [29,39], equal to 46.3 m^3/h and assume dot be satisfied by a mechanical ventilation system. V1 is the scenario corresponding to the minimum air change rate necessary to satisfy the regulation compliancy in building design. Occupancy is defined according to the Swiss norm SIA2024 [29], from 8:00 a.m. to 6:00 p.m. weekdays and constant through the year. The other scenarios have additional natural or mechanical ventilation strategies, described in Table 3. During the calibration phase of the virtual prototype, made thanks to the small test facility placed in Fribourg and according to the procedure describe in [40], the airflow rate due to natural ventilation has been measured as 50 m^3/h. However, in the software, the model has been built only as opening surface in direct contact with the external surface and the ventilation rate has not been controlled. However, calibration results showed that the virtual model has reliable and robust results (max error encountered below 1.5 °C, [41,42]).

Table 3. Ventilation scenarios used for the analysis.

Scenario	Basic Airflow	+	Mechanical Ventilation	Natural Ventilation
V1	46.3 m^3/h during occupancy (weekdays 8 a.m.–6 p.m.)	+	-	-
V2	as reference scenario	+	46.3 m^3/h from 2 to 6 a.m.	-
V3	as reference scenario	+	46.3 m^3/h if Tint-Text > 2 K and Tint > 21 °C	-
V4	as reference scenario	+	-	Open windows during occupied hours (weekdays 8 a.m.–6 p.m.)
V5	as reference scenario	+	-	Open windows 24/24 h

2.2.3. Risk Scenarios

Natural ventilation is hardly controllable, due to the variable represented by the occupants' use of the windows system. In standard dynamic simulations, a deterministic static approach is usually applied, overlooking the occupants' interactions or misuse of the building components [43,44]. Four risk scenarios have been introduced to encompass possible critical situations that might interfere with the effects of natural ventilation:

1. R1. Misuse of the blinds considered at 50% opened all day and night [45]
2. R2. Hot year in Fribourg, given by Meteonorm as result of the global warming projections from IPCC [46,47];
3. R3. Misuse of the openings (manual opening), which considers natural ventilation made by users only when internal temperatures are above 26 °C [45];
4. R4. Extreme risk scenario (combination of all risks).

Table 4 summarizes the ventilation scenarios used as reference and the risk associated to each risk scenarios, which are applied to V4 and V1, as they are by definition strictly correlated to natural ventilation and the study is focused on offices, which are more likely to have interactions between the mechanical system and the windows opening behavior during the working hours, when offices are occupied. V1 is used as reference for the ventilation strategy's comparison. Scenarios R1 and R3 are results of an extensive study project of the Swiss Energy Office [45], focused on the effective use of movable shading devices in offices and the relative impacts on indoor lighting. Scenario R3 is not applied to V1 as the ventilation strategy adopted does not include the windows opening. Scenario R2 represents a possible future warmer summer or a weather anomaly that creates an extraordinary hot summer, as defined by the climatic projections of the Intergovernmental Panel on Climate Change, scenario A1B [46,47]. The climatic difference between the typical meteorological year and the IPCC predictions are shown in Figure 2. The last scenario is the sum of each previous risk factor.

Table 4. Risk scenarios analysed.

Scenario	Basic Airflow	+	Risk Associated	Reference
R1	46.3 m^3/h (weekdays 8 a.m.–6 p.m.)	+	Blinds 50% opened 24 h	[45]
R2	46.3 m^3/h (weekdays 8 a.m.–6 p.m.)	+	Scenario A2 of future hot climates by IPCC—higher temperatures	[46,47]
R3	46.3 m^3/h (weekdays 8 a.m.–6 p.m.)	+	Windows totally open when Toutdoor > 26 °C	[45]
R5	46.3 m^3/h (weekdays 8 a.m.–6 p.m.)	+	Combination of all previous risk scenarios	[45–47]

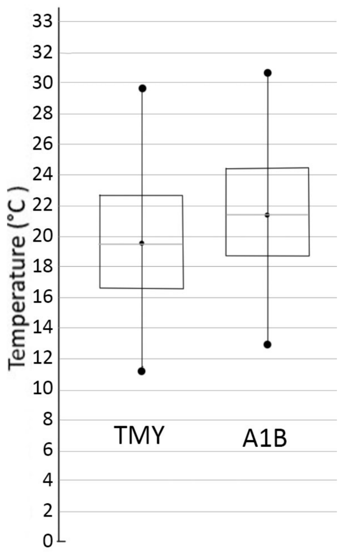


Figure 2. Comparison of the average dry-bulb temperature for the TMY climatic files and the future scenario A1 form IPCC.

3. Results

3.1. Indoor Comfort Provided

Hourly indoor temperatures given by the dynamic simulations have been evaluated for the local thermal comfort assessment. SIA 180:2014 [39] is used as reference for the analysis. The norm gives specific boundaries to evaluate thermal comfort: operative temperatures of every occupied hour should fall into the confidence interval identified by the running mean of external temperatures. As the norm suggests, the approach used to analyze the results is based on the concept of adaptive comfort, which better reflects the response of the human body to the thermal variations. The approach accounts for the acclimatization given by the previous days temperature, and it links together the external temperatures and the acceptable comfort threshold [39]. The running outdoor mean temperature [39] is defined as the 48-hour average external temperature

$$T_{rm}(t) = \frac{1}{N} \cdot \sum_{j=0}^{N-1} T_{ext}(t-j), \tag{2}$$

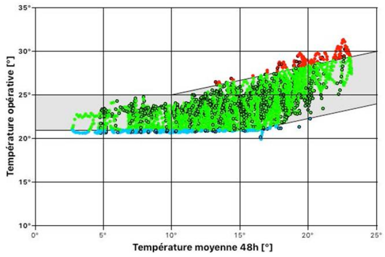
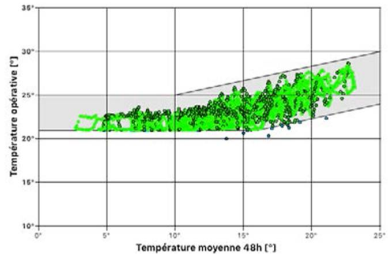
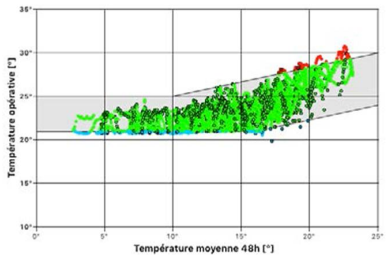
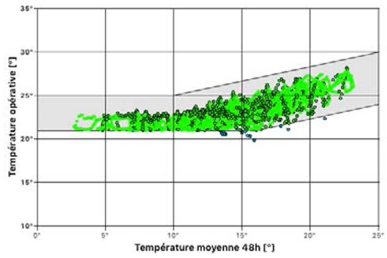
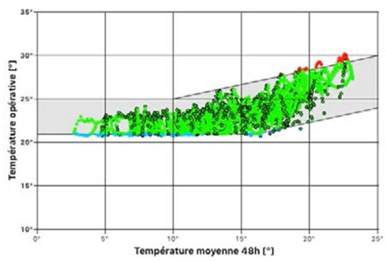
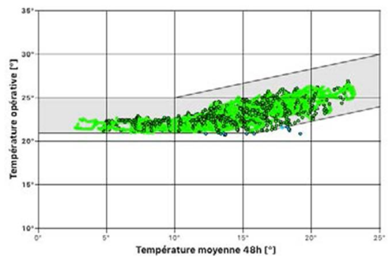
where $T_{rm}(t)$ is the moving average temperature at time $t = H$, $T_{ext}(t-j)$ is the external temperature during the hour $(t-j)$, and N is the number of hours considered [30]. The analysis considers the number of overheating hours, defined as the hours where operative temperature is not included in the running mean interval. SIA 180:2014 [39] states that all the occupied hours should be in the comfort zone, as defined above. Therefore, a scenario is considered comfortable and acceptable only when there is not any hour of overheating. Table 5 shows the overheating hours for each scenario and the maximum operative temperature achieved.

Table 5. Number of overheating hours for each scenario and, in brackets, maximum operative temperature in degree Celsius. Note that the overheating hours are calculated on the whole year and not only on the occupied hours.

TI	Ventilation Scenario				
	Scenario V1	**Scenario V2**	**Scenario V3**	**Scenario V4**	**Scenario V5**
TI1	743 (34)	712 (33.7)	591 (32.7)	25 (31.3)	13 (29.8)
TI2	689 (33)	636 (32.8)	493 (31.8)	9 (30.7)	5 (29.1)
TI3	648 (32.4)	592 (32)	401 (31.2)	4 (30.1)	2 (28.7)
TI4	666 (30.3)	616 (30)	326 (29.3)	0 (28.7)	0 (27.8)
TI5	613 (29.8)	544 (29.4)	276 (29.6)	0 (28.2)	0 (27.1)
TI6	533 (28.5)	434 (28)	128 (27.1)	0 (26.9)	0 (25.9)

Results show the influence of thermal mass and ventilation on the overheating risk of an office building placed in Fribourg (CH). It is possible to notice that the ventilation strategy is more influent than the thermal mass, as the number of occupied hours outside the comfort range is much lower when natural ventilation is applied. Thermal mass becomes essential in mitigating the discomfort when insufficient ventilation strategies are applied: although the number of overheating hours is still high, the maximum temperature achieved is up to 5.7 °C lower. This result indicates that thermal mass is able to smooth the heat peaks, especially during summer, but it is less efficient during the middle seasons, when the threshold given by the running mean temperature is likely to be lower and, therefore, also relatively low temperature (lower than 28 °C) can be considered overheating. The total amount of overheating hours indicates that natural ventilation is capable to reduce the overheating risk, regardless the typology of construction involved. Instead, the maximum operative temperature achieved shows that thermal mass is essential to reducing the operative temperatures. In order to couple the two effects and reduce the overheating risk in terms of both duration and intensity, it is essential to find a way to integrate the appropriate level of thermal inertia with ventilative cooling strategies. Considering that thermal mass is the most influencing strategy on the final design of a building, due to the amount of material required to achieve the different level (Table 2), the scenario that optimized the reduction of temperature and the TI level is represented by TI4. Middle levels of TI allow to reduce the operative temperature of almost 4 °C. This is particularly clear in Table 6 where the adaptive comfort graph according to SIA 180 [39] is plotted for the different TI scenarios and ventilation V4 scenario. From TI4, there is not overheating risk. The building code does not accept exception and only the scenario with 0 overheating hours are compliant.

Table 6. Adaptive comfort diagram with indication of discomfort hours.

Scenario	Comfort Diagram	Scenario	Comfort Diagram
TI1 + V4		TI4 + V4	
TI2 + V4		TI5 + V4	
TI3 + V4		TI6 + V4	

3.2. Risk Scenarios Results

We considered the possible misuse of the systems by users (blinding misuse in scenario R1 and windows-opening misuse in scenario R3) and the weather uncertainty (scenario R2). The combination of all these criticisms creates the scenario of maximum risk. The risk scenarios are used to create a new set of simulations, useful to understand the influence of these uncertain parameters on the results. The risk-analysis has been applied to scenario V4, combined with all the thermal mass levels, to represent a typical situation in offices: hygienic mechanical ventilation enhanced by natural ventilation during the occupied hours. The introduction of these risk scenarios has a big influence on the results, as it shifts all the results far above the acceptable comfort threshold; for this reason, the cooling needs have been used as a more appropriate indicator for the influence of thermal mass during the risk scenarios.

Figure 3 shows the influence of the risk factors on the cooling requirements of the office building taken as a case study. The effects of R4 (maximum risk) is reduced by high TI levels coupled with natural ventilation: the maximum operative temperatures from a lightweight construction (TI1) to a heavyweight construction (TI6) can be reduced consistently. In scenario R2, the cooling needs increase up to a factor of 2, showing the high uncertainty related to simulations in relation to the climatic weather file used. This clearly underlines the importance of considering this variable during the design stage of a building, which should encompass for possible weather anomaly and future hotter summer. In relation to the possible misuse of the building's equipment by users, it is important to notice that blinds misuse (scenario R1) is more critical than windows opening misuse (scenario R3). This shows that in an office building, the solar gains can significantly contribute to increase the internal temperature, leading to a situation of overheating. Table 7 shows the maximum operative temperature simulated with scenario V4 and V1 in relation of all the risks. The comfort threshold for natural ventilation depends on the running mean temperatures (as described in the previous section). However, temperatures above 40 °C are associated with health risk for human beings. Results clearly show the influence of thermal mass in mitigating the heat peaks and stabilizing indoor temperatures: the difference between the indoor operative temperature achieved in TI1 and TI6 ranges from 4 °C (V4 + R3) up to 9 °C (V1 + R4). Moreover, the effects of the additional mass in the construction are more visible when the scenario is more critical (e.g., risk combination R4 or inadequate ventilation V1), underlining the importance of thermal mass for resilient design. Ventilation is found to be beneficial in all the scenarios, regardless the risk and the thermal mass level. Table 8 shows the distribution of the hourly temperature over the summer period: on the vertical axis, there are the hours of the day and, on the horizontal axis, the days of summer months. The graphs are shown for TI1 and TI6 in case of V4 and R4. This choice is related to the necessity of understanding the role of TI when all risks are applied. From the figure, it is possible to notice that thermal inertia reduces not only the hours of overheating (distribution) but also the intensity of the overheating (color).

Table 7. Maximum operative temperatures calculated for each TI scenario in relation to V4 and V1. Results are shown for the basic scenario and for each risk factor applied.

TI Scenario	Tmax °C		Tmax °C R1		Tmax °C R2		Tmax °C R3		Tmax °C R4	
TI	V1	V4	V1	V4	V1	V4	V1	V4	V1	V4
TI1	34	31.3	39.8	35.4	39	36	-	31.9	43.8	40.2
TI2	33	30.7	38.4	34.8	37.6	35.5	-	31.2	42.2	39
TI3	32.4	30.1	37.5	34	36.8	34.6	-	30.8	40.9	38.2
TI4	30.3	28.7	34.6	31.5	33	31.8	-	29.2	37.5	35.3
TI5	29.8	28.2	33.8	30.6	32.2	30.8	-	28.8	36.6	34.6
TI6	28.5	26.9	31.7	28.8	31	28.3	-	27.2	34.8	31.8

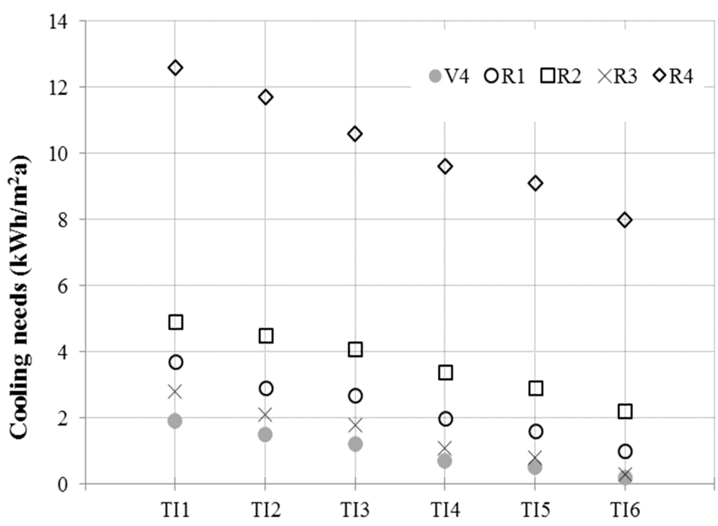
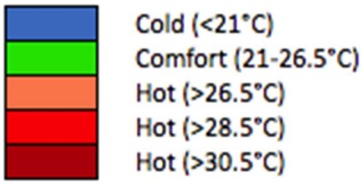
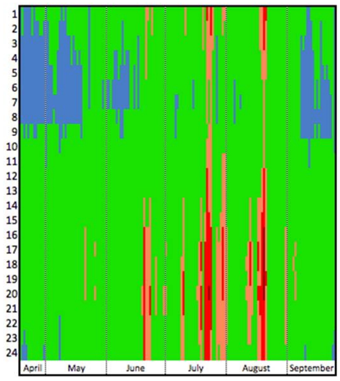
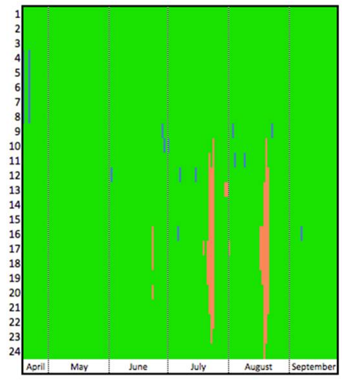
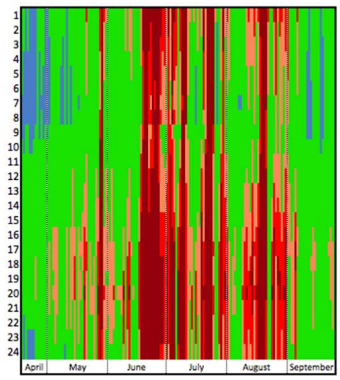
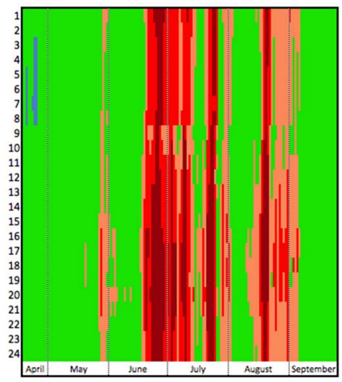


Figure 3. Cooling needs calculated for the combined scenarios: V4 and risk factors. TI effects ranges from 12% (R4) up to 62% (R3), considering the difference between TI1 and TI6.

Table 8. Temperature distribution over the summer for scenarios.



Scenario	Comfort diagram	Scenario	Comfort Diagram
TI1 + V4		TI6+V4	
TI21 + R4		TI6+R4	

An interesting observation can be made when considering R4: the effects of the risk-factors sum is not equivalent to the sum of the effects of each risk factor. The reason is to be sought in the interdependences between the different risk events and the building's response. Building behavior is hardly predictable and it depends on a number of different parameters, among those there are solar gains, internal heat gains, the envelope and its materiality, and external and internal climates. These parameters are not independent, but strictly correlated one to the other, making it extremely difficult to separate the effects of each one in a multidimensional transient system. In R4, the building is respond to different non-optimal scenarios, which aggravate the overall context. For example, the warmer climatic conditions make even worse the effects of the internal gains captured by the open blinds, warming up the indoor air. At the same time, windows open when outside air is already hot (>26 °C) means that the system is not able to dissipate the overheating. Although R4 is highly critical, TI effects are more influent, showing their high potential in mitigating critical situations.

4. Conclusions

In this paper, we presented a preliminary study on the influence of thermal mass and ventilation on the thermal comfort provided in a standard office building in Fribourg (Switzerland), designed according to the actual building code, in the framework of the smart living building. The analysis included different thermal mass levels, typologies of construction, ventilation strategies, and several risk scenarios, where the standardized assumptions for thermal simulations have been changed to account for critical situations. The smart living building is used as a case study and framework of the analysis. Results show the importance of natural ventilation as a passive cooling strategy, regardless the construction's typology. Thermal mass, instead, is essential to stabilize indoor temperatures, however its potential is maximized when coupled with natural ventilation strategies, as alone it is not sufficient to keep the indoor environment within comfort thresholds defined by the norm. Considering the high environmental impacts often associated with thermal mass, a future research stream will aim to identify the benefits of heavyweight construction on thermal comfort balancing the embodied impacts. Previous studies have highlighted the necessity to integrate this balancing method form the early design stage [35] and the same approach will be integrated and developed including the thermal comfort criteria.

Among the different mechanical ventilation profiles, the most effective is the one based on temperature gradient. Considering the risks scenarios, instead, it is clear that thermal mass is a way to reduce the associated cooling loads; however, the relevance of introducing a risk assessment during the design phase is highlighting by the significant increase of maximum operative temperatures achieved in all scenarios. Moreover, the impacts of the combined scenarios are almost twice as heavy compared to the sum of the single scenarios, indicating that a one-factor analysis is not sufficient to assess the relevance of the variations introduced by the risk factors.

The research framework and the building code used framed the analysis on reliable references, however, they also represent a limitation of the study, as the results are strictly dependent upon the assumptions made. The relatively small amount of risk scenarios do not allow to generalize the results to a broader set of scenarios, however, the research is now focusing in understanding how to create additional risk scenarios that could improve the reliability of the study. A better definition of the risk scenarios matrix could allow also to apply the same methodology for a wider range of climatic conditions, analyzing the resilience of different building typologies across several cultural, social, and climatic contexts. This next step of the research aims to define the intensity of resilience required of buildings to guarantee thermal performance during their lifetime even if subjected to risk events, e.g., future warmer climates.

Author Contributions: A.B. and T.J. conceived and designed the experiments; A.B., F.F. and J.B. performed the experiments; T.J. analyzed the data; A.B. wrote the paper; T.J. reviewed the manuscirpt.

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