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Influence of raised floor on zone design cooling load in commercial buildings

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ABSTRACT
The installation of a raised floor system can change the thermal behaviour of the building by reducing the interaction between the heat gains and the thermally massive concrete slab. In this study, the influence of the raised floor on the summer design day zone cooling load profile is evaluated for an office building located in San Francisco by using the whole-building energy simulation program, EnergyPlus. The zone cooling load profiles and the thermal performance with and without the raised floor are compared and analyzed. The effects of structure type, window-to-wall ratio and the presence of carpet on the thermal behaviour of the raised floor are also investigated. The results show that the mere presence of the raised floor largely affects the zone cooling load profile and the peak cooling load over the range of -7% to + 40%. The most significant parameters are the zone orientation, i.e. the exposure to direct solar radiation, and the presence of floor carpeting. If carpeting is present, commonly used in U.S. office buildings, the overall impact on zone peak cooling load is reduced, ranging from 0 to 5% greater for the raised floor than without it. Without carpet the peak cooling load is 4% greater with raised floor than without it in the north zone, 22% in the east and west zones, and 12% in the south zone.

KEYWORDS
Raised floor
Cooling load
HVAC sizing
Access floor
Ventilation

INTRODUCTION

Raised floor systems, also known as access floor systems, have received increasing attention and are now common features in commercial buildings [1]. A raised floor system is the array of elevated removable floor panels (typically cement-filled, 60 cm x 60 cm x 3 cm [24 in. x 24 in. x 1.3 in.]) installed on top of the building concrete slab. The plenum space between the concrete slab and the raised floor typically provides the building services such as electrical supply, cables, data and security.

A raised floor system provides a variety of benefits compared to a conventional building. It provides improved flexibility to easily reconfigure workstations and associated building services while minimizing materials and labour costs [1]. In addition, advanced cooling technologies such as underfloor air distribution (UFAD) can be incorporated [2], which have the potential to improve energy performance and ventilation effectiveness while reducing the amount of ductwork and floor-to-floor heights compared to conventional overhead systems. Nevertheless, research studies focusing on the thermal behaviour of raised floor systems have not been extensively performed.
The raised floor serves as a separation between the room and the thermally massive concrete slab, potentially changing the thermal behaviour of the entire building structure. Since it is well-known that building thermal mass plays an important role in energy and comfort performance, the presence of the raised floor may possibly have an impact on building thermal performance. Rock et al. [3] conducted a sensitivity analysis to investigate the

influence of various parameters such as convective heat transfer coefficients and surface conditions on the heat transfer in underfloor and return plenums. It was observed that the peak cooling load turned out to be relatively sensitive to the surface convection coefficients, while the overall energy was not very sensitive to the variables. Lehmann et al. [4] observed a reduction of the maximum permissible total heat gain due to the existence of a raised floor, demonstrating the decoupling effect of a raised floor system. However, it did not include a detailed analysis on this issue, since the main topic of the study was not raised floors. A further literature review does not reveal any other relevant work whose main topic is the impact of raised floors on energy performance.
In a UFAD system the cool supply air flowing through the plenum is exposed to heat gain from both the concrete slab in a multi-story building and the raised floor panels. The magnitude of this heat gain, often referred to as thermal decay, can be quite high, resulting in undesirable temperature gain to the supply air in the plenum. While the amount of heat entering the underfloor plenum is not expected to change the magnitude of the cooling load that must be removed at the system level, it does directly influence the required zone cooling airflow quantity by reducing the amount of heat gain that must be removed by room air extraction [5] [6]. Properly controlled UFAD systems under cooling operation produce temperature stratification in the conditioned space resulting in higher temperatures at the ceiling level that change the dynamics of heat transfer within a room, as well as between floors of a multi-story building [7]. In a UFAD system the problem is more complex than the one presented in this paper; it is difficult to isolate the influence of the raised floor from the interaction between thermal decay in the plenum from temperature stratification in the room. In this study the influence of the raised floor on the cooling load for a UFAD system was not included because the topic will be covered in a future paper.

The purpose of this study was to analyze, by means of energy simulations with EnergyPlus, the influence of the raised floor on the zone cooling load profile in a non-UFAD system for a prototype office building on a summer design day in San Francisco. The zone cooling load profiles and the thermal performance with and without the raised floor were compared and analyzed. The influence of structure type, window-to-wall ratio and presence of carpet on the detailed thermal behaviour of the raised floor has also been investigated.

METHODS

The input data of the energy simulation are reported below.[1].

Building location and weather data

An office building located in San Francisco was modelled. The weather in San Francisco is characterized as a warm and marine climate. To calculate the zone cooling load profile for each zone of the building, simulations were conducted for 38 cases for a summer design day. ASHRAE 1% summer design conditions were assumed [8].

Description of the office building

A three-story prototype office building with a rectangular shape (52.8 m x 35.2 m) and aspect ratio of 1.5 was chosen for this study. The floor plate size is 1,858 m^2 (total floor area is 5,574 m^2) and each floor is composed of 4 perimeter zones, an interior zone and a service core, which represent approximately 40%, 45% and 15% of the floor area, respectively, as shown in Figure 1. The floor to floor height is 3.96 m and the return plenum height is 0.6 m. The building's exterior wall height does not change when the raised floor is added. The raised floor height is variable (0.1 m, 0.3 m or 0.46 m). In the baseline case, no raised floor exists.

[1] The European standard 15265-2006 [9] recommends a format for reporting the input data of an energy simulation. The following presentation of input data complies with the guidance in the standards.

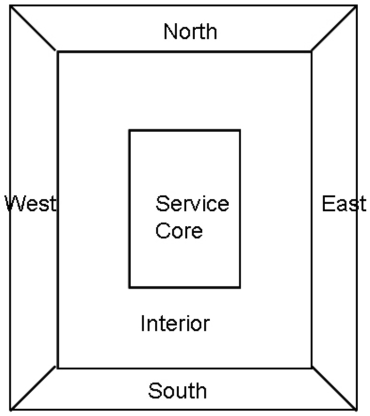


Figure 1 Floor plan of the simulated building.

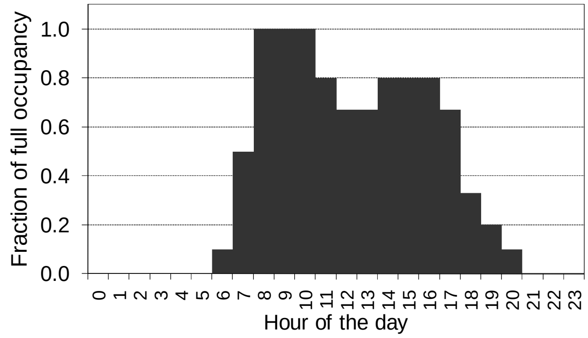


Figure 2. Occupancy profile.

Strip windows are evenly distributed in the walls and their location does not change if the raised floor is present. The baseline window-to-wall ratio (WWR) is 40%, meaning that 40% of the wall area is covered with windows. Different WWRs are achieved by varying the window height only. The non-north oriented windows are composed of a 6 mm external sun protection glass pane, 13 mm of air and a 6 mm internal clear glass pane, the north oriented windows are composed of a 4 mm external low emissivity glass pane, 13 mm of air and a 6 mm internal clear glass pane. The non-north oriented windows have an overall U-value of 1.64 $WK^{-1}m^{-2}$, a g-factor, or Solar Heat Gain Coefficient, equal to 0.387, and a light transmittance equal to 0.702. The north oriented windows have an overall U-value of 1.75 $WK^{-1}m^{-2}$, a g-factor, or Solar Heat Gain Coefficient, equal to 0.568, and a light transmittance equal to 0.763. Three construction types were simulated, light-weight, medium-weight and heavy-weight. The construction characteristics are summarized in Table 1. For the properties of the material used, refer to chapter 18, table 18 of ASHRAE Handbook - Fundamentals [8].

Table 1 Characteristics for the construction for the light-weight, medium-weight and heavy-weight construction class.

Construction Class	Exterior Wall	Ceiling/Floor	Partition	Roof	Ground floor slab
Light-weight (LW)	0.8 mm steel siding, 50 mm insulation board, 50 mm air space, 19 mm gypsum	100 mm of lightweight concrete, ceiling air space, acoustic tile	19 mm gypsum, 50 mm air space, 19 mm gypsum	100 mm of lightweight concrete, ceiling air space, acoustic tile	100 mm of lightweight concrete, ceiling air space, Heavy insulation
Medium-weight (MW)	100 mm brick, 50 mm insulation board, 50 mm air space, 19 mm gypsum	100 mm of heavyweight concrete, ceiling air space, acoustic tile	19 mm gypsum, 50 mm air space, 19 mm gypsum	100 mm of heavyweight concrete, ceiling air space, acoustic tile	100 mm of heavyweight concrete, ceiling air space, Heavy insulation
Heavy-weight (HW)	100 mm brick, 200 mm of heavyweight concrete, 50 mm insulation board, 50 mm air space, 19 mm gypsum	200 mm of heavyweight concrete, ceiling air space, acoustic tile	19 mm gypsum, 200 mm heavyweight concrete, 19 mm gypsum	200 mm of heavyweight concrete, ceiling air space, acoustic tile	200 mm of heavyweight concrete, ceiling air space, Heavy insulation

Table 2 Overall U-factors (W/m^2K) for each of the construction type of the light-weight, medium-weight and heavy-weight construction class.

Construction Class	Exterior Wall	Ceiling/Floor	Partition	Roof	Ground floor slab
Light-weight (LW)	0.49	1.45	2.59	1.45	0.27
Medium-weight (MW)	0.47	1.82	2.59	1.82	0.28
Heavy-weight (HW)	0.45	1.66	2.94	1.66	0.28

The effect of thermal mass was taken into account. Internal mass, e.g. furnishings, was simulated with 25 mm of wood with an area equal to 50% of the floor area. The wood has a conductivity of 0.15 W/(m K), a density of 608 kg/m^3, a specific heat of 1.63 kJ/(kg K) and a thermal mass of 25.35 $kJ/(m^2K)$. Internal mass increases the amount of surface area that can participate in radiative and convective heat exchanges and it also adds thermal mass to the zone. These two changes can affect the time response of the zone cooling load [8]. The raised floor properties were taken from a common, commercially available product. The raised floor has a thickness of 0.025 m, a conductivity of 0.14 W/(m K), a density of 1185 kg/m^3, and a specific heat of 0.669 kJ/(kg K).

Internal temperature, ventilation and infiltration rate, and HVAC system

From 7:00 till 18:00 the cooling system controls the internal air temperature to a cooling temperature setpoint of 24°C. During the nighttime the temperature set-back is 40°C. At full occupancy the occupant density is 1 person every 10 m^2 of floor area. There are no people in the service core zone. The total number of people at full occupancy is 459 for the whole building. The infiltration was assumed equal to 0.2 ACH.

The ventilation and the heating and cooling systems were not modelled because the simulation aim was to investigate the influence of the raised floor on the zone cooling load profile. The humidity level was monitored but not controlled. The zone air temperature was controlled and the zone cooling load profile was calculated using the EnergyPlus function “ZoneHVAC:IdealLoadsAirSystem” [10]. This object provides the required supply air capacity to each zone at user specified temperature and humidity ratio to calculate the heating and cooling loads. All the zones are well mixed and the volume below the raised floor was not conditioned. This means that the results cannot be directly extrapolated and applied to a UFAD system where the air is supplied through the underfloor plenum and there is vertical temperature stratification in the zone. A future study will analyze the difference in zone cooling load between UFAD and a well mixed system by taking into account the ventilation and the operation of the interactive HVAC systems.

Internal heat gains and occupancy

The 459 occupants contribute to both sensible and latent heat load in the building. The activity level of the occupants is 1.2 met (1 met = 58.15 W/m^2), and the total heat produced per occupant is thus around 125 W. The balance between sensible and latent heat is calculated by the software. The occupants’ presence in the building varies according to Figure 2. In this paper, the fraction of full occupancy was defined as the ratio of the actual number of occupants present at their desks to the maximum number of occupants the room was designed to accommodate. The occupancy behaviour profile as shown in Figure 2 is patterned after the European standard EN 15232 [11]. The fractions of full occupancy were slightly modified in order to better describe the typical working schedule in San Francisco. At maximum occupancy on each floor there are 14 occupants in the East and West zones, 22 in the North and South zones, and 81 occupants in the interior zone. The heat load due to office equipment is 6 W/m^2. According to ASHRAE [8], this value corresponds to a “light load office”. The equipment loads follow the schedules of the occupants. The lighting load is 10.8 W/m^2 and it follows the load shown in Table 3.

Table 3. Lighting load during weekdays.

Time	% Lighting
01:00-5:59	5
06:00-7:59	10
08:00-8:59	30
09:00-12:59	100
13:00-13:59	80
14:00-17:59	100
18:00-18:59	50
19:00-20:59	30
21:00-22:59	20
23:00-0:59	10

Simulation software

A robust building energy simulation program, EnergyPlus version 3.1.0.027, was used for the simulations. EnergyPlus is a whole-building energy simulation program developed for the U.S. Department of Energy [10]. It allows for performing simulations of the building and the HVAC system as a whole. It calculates the thermal loads to be satisfied and predicts HVAC system operation needed to fulfil the required comfort conditions. EnergyPlus was selected because it is a heat balance based simulation program and the heat balance method is the current industry standard method for calculating space loads [8]. For more information about validation of the EnergyPlus program, see [12].

Simulated cases

The purpose of the study was to investigate the influence of a raised floor on the zone cooling load profile for design day conditions for a building with a conventional overhead air distribution system. Three parameters (structure type, window-wall ratio (WWR), presence of carpet) affecting the load and the thermal response of the building were studied. The simulated cases are listed in Table 4.

Three structure types were investigated: light-weight, medium-weight and heavy-weight. The construction characteristics are reported in Table 1 and Table 2. The thermal mass affects the amplitude and time response of the building to the heat gain. Three window-to-wall ratios were investigated, ranging from 20% to 60%.

It is common to combine the raised floor with carpet because it improves the acoustic quality of the environment and helps to save energy in winter by reducing discomfort caused by cold feet [8]. The carpet has a thickness of 12.7 mm, a conductivity of 0.06 W/(m K), a density of 288 kg/m^3, a specific heat of 1.38 kJ/(kg K) and a thermal mass of 5.11 kJ/(m^{2}K).

The influence of floor height on zone cooling loads was tested with three independent runs. The raised floor height was simulated for the following three values: 0.10 m (4 in.), 0.30 m (12 in.) and 0.46 m (18 in.). The lowest plenum height (0.10 m) is a typical value for a raised floor in an office application when the plenum is used only for cable management and not for air distribution.

Table 4 Simulated cases

Case[a]	Structure Type	Window-to-Wall Ratio [%]	Carpet	Height of Raised Floor [m]
1	Light	20	Yes	0.30
2	Medium	20	Yes	0.30
3	Heavy	20	Yes	0.30
4	Light	20	No	0.30
5	Medium	20	No	0.30
6	Heavy	20	No	0.30
7	Light	40	Yes	0.30
8	Medium	40	Yes	0.30
9	Heavy	40	Yes	0.30
10	Light	40	No	0.30
11	Medium	40	No	0.30
12	Heavy	40	No	0.30
13	Light	60	Yes	0.30
14	Medium	60	Yes	0.30
15	Heavy	60	Yes	0.30
16	Light	60	No	0.30
17	Medium	60	No	0.30
18	Heavy	60	No	0.30
19[b]	Medium	40	No	0.10
20[b]	Medium	40	No	0.46

[a] For each of the cases, the same building with and without the raised floor was simulated.
[b] In these cases, the building without the raised floor was not simulated.

RESULTS

Simulation results for the design day peak cooling load for each zone (North, East, South, West, and Interior) and floor (Ground, Middle, and Top) for the 36 simulated cases are reported in Table 5 and shown as a box-plot in Figure 3. A boxplot is a way of graphically summarizing a data distribution. In a boxplot the horizontal line in the box shows the median. The bottom and top of the box show the 25th and 75th percentiles, respectively. The horizontal line joined to the box by the dashed line shows either the maximum or 1.5 times the interquartile range of the data, whichever is the smaller. Points beyond those lines are outliers. The interquartile range is the difference between the 25th and 75th percentiles [13]. The values listed in the table represent the maximum cooling load occurring during the design day for each zone and floor. The Shapiro-Wilk normality test ($W = 0.91$, $p\text{-value} < 0.001$) indicates that design day peak cooling load does not have a normal distribution, thus the mean and standard deviation cannot be used to describe its distribution. For all the simulated cases the zone peak cooling load varied from 20 W/m^2 (minimum) to 172 W/m^2 (maximum), with a median equal to 51 W/m^2. Table 5 indicates that, in general, the cooling load is higher in the east, south and west zones than in the interior and north zones due to the incident solar radiation.

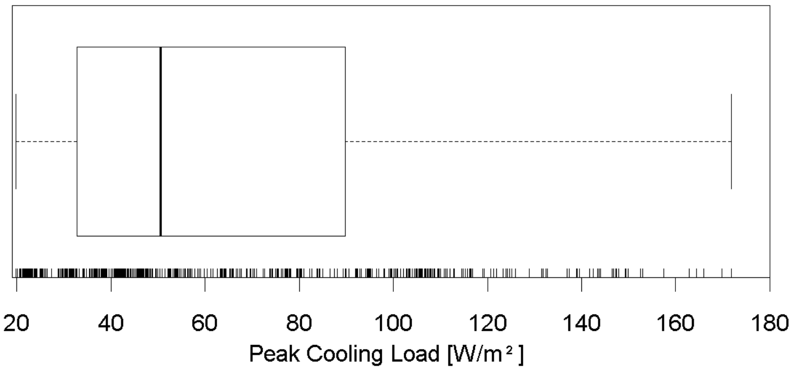


Figure 3 Box-plot for the Peak Cooling Load calculated for each zone (North, East, South, West, and Core) and floor (Ground, Middle, and Top) for the 36 simulated cases (Table 4).

Table 5 Design day peak cooling load for each zone (North, East, South, West and Interior), floor (Ground, Middle, and Top) and for the 36 simulated cases (case 19 and 20 are not included here).

		Peak Cooling Load With Raised Floor					Peak Cooling Load Without Raised Floor				
Case	Floor	North	East	South	West	Interior	North	East	South	West	Interior
		[W/m^2]	[W/m^2]	[W/m^2]	[W/m^2]	[W/m^2]	[W/m^2]	[W/m^2]	[W/m^2]	[W/m^2]	[W/m^2]
1	GF	25	47	52	64	22	26	48	53	66	22
1	MF	26	47	52	64	22	26	49	54	66	22
1	TF	42	44	65	83	40	43	44	67	85	41
2	GF	24	40	46	56	22	24	42	48	59	21
2	MF	25	41	47	57	22	25	44	48	60	22
2	TF	42	46	62	76	41	43	46	64	80	42
3	GF	22	41	44	52	21	23	42	45	54	20
3	MF	24	42	46	53	22	24	44	46	56	21
3	TF	30	41	48	60	30	31	43	49	63	30
4	GF	25	42	50	59	22	26	47	52	64	22
4	MF	26	43	51	59	22	26	48	52	64	22
4	TF	41	44	63	76	39	43	44	66	83	41
5	GF	23	35	44	47	22	24	41	47	57	22
5	MF	24	36	45	48	22	25	43	48	58	22
5	TF	40	46	58	63	39	43	46	63	77	42
6	GF	22	36	41	44	21	22	41	44	53	20
6	MF	23	37	42	45	22	24	43	46	54	21
6	TF	30	36	45	52	29	31	42	48	62	29
7	GF	32	76	84	106	23	33	80	87	110	23
7	MF	33	76	84	106	23	33	80	87	109	23
7	TF	48	66	92	124	42	49	69	95	129	42
8	GF	30	70	78	98	23	31	75	82	104	22
8	MF	31	71	78	98	23	32	76	83	105	23
8	TF	48	61	88	117	42	50	66	92	125	43
9	GF	29	69	75	92	21	29	73	78	98	21
9	MF	30	70	76	93	23	31	74	79	99	22
9	TF	36	68	75	100	31	36	72	79	107	30
10	GF	31	67	78	95	23	32	77	84	106	23
10	MF	32	67	78	95	23	33	78	84	106	23
10	TF	46	57	89	111	40	49	67	93	125	42
11	GF	29	56	70	78	23	31	73	80	101	23
11	MF	30	56	70	78	23	32	74	80	101	23
11	TF	45	54	81	93	40	49	64	91	121	43
12	GF	27	57	65	74	22	29	71	76	95	21
12	MF	29	58	66	74	23	30	73	77	96	22
12	TF	34	55	67	80	30	36	70	77	103	30

13	GF	38	106	115	147	24	39	111	119	153	24
13	MF	39	105	115	147	24	40	111	119	152	24
13	TF	54	94	121	164	43	55	100	126	172	44
14	GF	37	100	110	139	24	38	108	116	149	23
14	MF	37	100	110	139	24	39	109	117	149	24
14	TF	54	90	116	157	43	56	98	124	170	44
15	GF	35	97	106	132	22	36	103	111	142	21
15	MF	36	98	107	133	23	37	105	112	142	22
15	TF	41	94	105	139	32	42	102	111	150	31
16	GF	37	92	107	132	24	39	108	116	148	24
16	MF	38	92	107	132	24	39	108	116	147	24
16	TF	52	81	114	146	41	55	96	123	166	43
17	GF	34	77	95	108	24	38	105	113	144	24
17	MF	35	77	94	108	24	38	106	113	143	24
17	TF	50	67	104	122	41	55	95	121	163	44
18	GF	33	77	90	103	23	35	101	109	137	22
18	MF	34	78	90	103	24	37	103	109	137	23
18	TF	39	74	88	107	31	42	99	108	144	31

Figure 4 presents two typical zone cooling load profiles for the five zones with and without the raised floor. The values are taken from the middle floor Case 11 from Table 4 with medium-weight structure, 40% window-to-wall ratio, no carpet, and 0.30 m raised floor height. These profiles were selected because they clearly show the difference caused by the presence of the raised floor on the zone cooling load. As expected, the cooling profile in the interior zone follows the internal heat load, i.e. people and equipment, and in the perimeter zones the profile is affected by the solar radiation. The peak load in the east zone is reached around ten o'clock, in the south zone around 13:00 when the raised floor is present and around 15:00 when there is no raised floor. In the West zone the peak cooling load is obtained around 17:00. The zone cooling load profiles for the cases with and without the raised floor are different for zones exposed to solar radiation. With a raised floor the peak zone cooling load is higher in all perimeter zones.

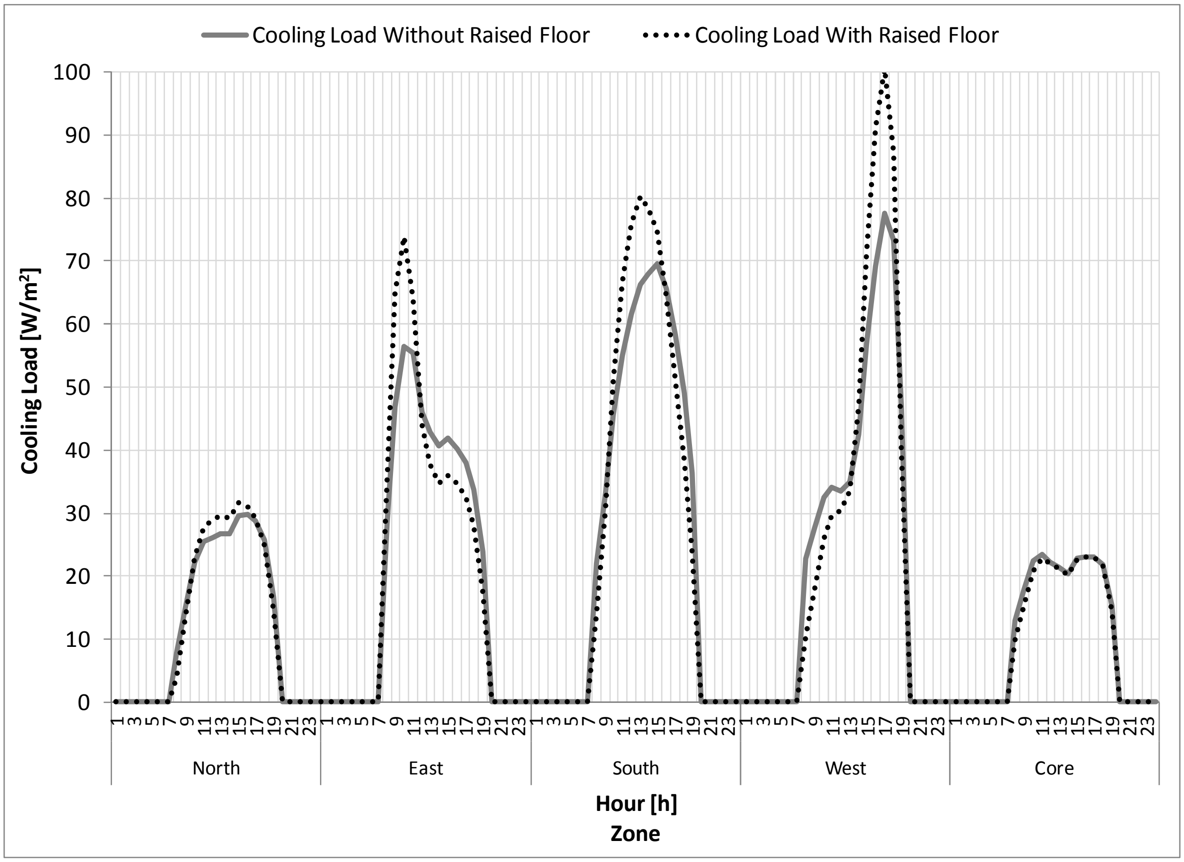


Figure 4 Cooling load profiles obtained with and without the raised floor for case 11 (Table 4) for the middle floor. Other assumptions: medium-weight, 40% window-to-wall ratio , no carpet, and 0.30 m raised floor height.

Table 6 Design day peak cooling load for each zone (North, East, South, West and Interior), floor (Ground, Middle, and Top) and for the cases 11, 19 and 20.

Case	Floor	Raised Floor Height [m]	Peak Cooling Load With Raised Floor North [W/m²]	East [W/m²]	South [W/m²]	West [W/m²]	Interior [W/m²]
19	GF	0.10	31	73	80	101	23
11	GF	0.30	31	73	80	101	23
20	GF	0.46	31	73	80	100	23
19	MF	0.10	32	74	80	101	23
11	MF	0.30	32	74	80	101	23
20	MF	0.46	32	74	80	101	23
19	TF	0.10	49	64	91	121	43
11	TF	0.30	49	64	91	121	43
20	TF	0.46	49	64	90	120	43

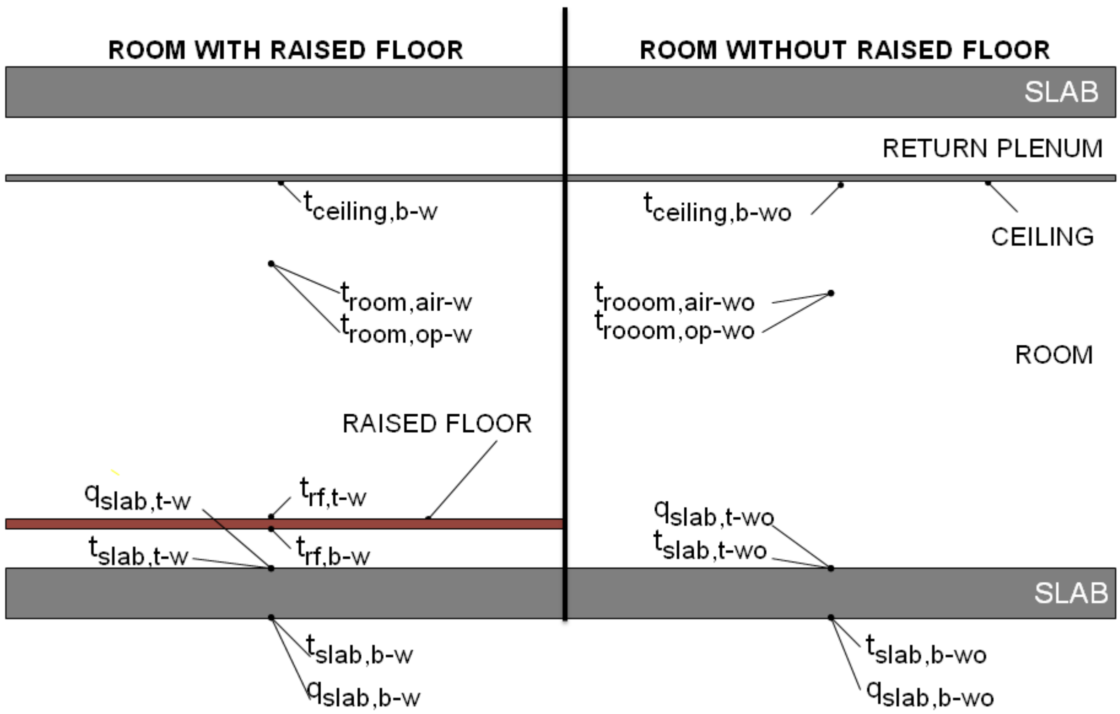
The influence of the raised floor height (0.10 m, 0.30 m and 0.46 m) on the zone cooling load was tested in the Cases 11, 19 and 20. The peak cooling load for each zone and floor is reported in Table 6. From the table can be deduced that the floor height does not affect the peak cooling load. An analysis of the zone cooling load profiles confirmed this conclusion.

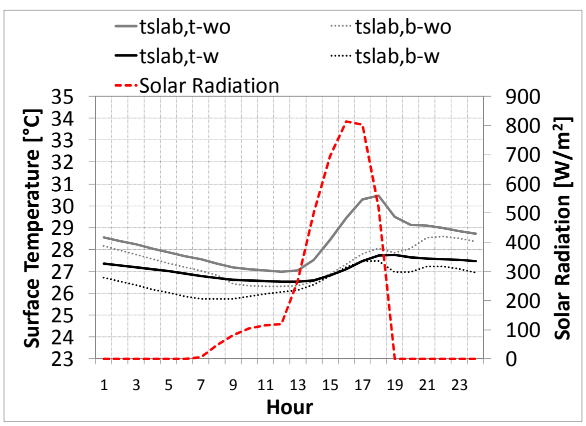
DISCUSSION

In this section we discuss why the presence of the raised floor increases the zone cooling load in the perimeter zones exposed to solar radiation, what is the magnitude of this effect, and which parameters have the greatest influence.

Influence of raised floor on zone cooling load

The instantaneous zone cooling load is the rate at which heat energy is convected to the zone air at a given point in time. Computation of zone cooling load is complicated by the radiant exchange between surfaces, furniture, partitions, and other mass in the zone. Most heat sources transfer energy by both convection and radiation. Radiative heat transfer introduces a time dependency to the process that is not easily quantified. Radiation is absorbed by thermal masses in the zone and then later transferred by convection into the space. This process creates a time lag and dampening effect. The convective portion, on the other hand, is immediately transformed into cooling load in the hour in which that heat gain occurs [8]. For a given amount of incident sunlight, thermally lightweight buildings will heat up more than heavyweight buildings. This is because they have a lower thermal storage capacity. This means that lightweight buildings will reemit their heat energy back into the space much quicker than buildings with a higher thermal mass. The existence of a raised floor has the effect of transforming the primary solar absorbing surface from a heavyweight slab into a relatively lightweight floor panel, thereby increasing the instantaneous cooling load in the zone. This phenomenon is shown in Figure 6 and Figure 7 for Case 11, Middle floor, West zone; the relevant temperatures and heat fluxes of the phenomenon are identified in Figure 5. Figure 6 shows the top ($t_{slab,t-wo}$ and $t_{slab,t-w}$) and bottom ($t_{slab,bwo}$ and $t_{slab,b-w}$) surface temperatures of the slab with and without the raised floor. $t_{slab,t-wo}$ is always higher than $t_{slab,t-w}$ and it varies more than $t_{slab,t-w}$. The same pattern can be seen for the bottom temperatures. Direct solar gain causes a higher surface temperature and more rapid response for the raised floor compared to the slab. Figure 7 shows the top ($q_{slab,t-w}$ and $q_{slab,t-wo}$) and bottom ($q_{slab,bw}$ and $q_{slab,b-wo}$) slab surface heat fluxes with and without the raised floor. When the heat flux is positive it means that the slab is releasing heat into the environment, when it is negative it means that slab is absorbing heat. One of the benefits of slab mass is to reduce cooling load by storing heat during the daytime when the HVAC system is operating and releasing it at night. The top surface heat flux for the case without the raised floor, $q_{slab,t-wo}$, is more negative than $q_{slab,t-w}$ during the day and higher during the night, this mean that when there is no raised floor the slab stores a greater amount of heat during the day. This is the reason why the zone cooling load for the case without the raised floor is lower than the case with the raised floor.





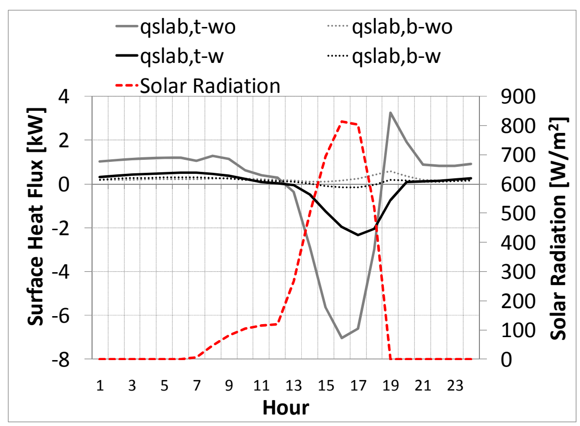


Figure 6 Top and bottom slab surface temperatures with and without the raised floor for west zone, middle floor of Case 11.

Figure 7 Top and bottom slab surface heat fluxes with and without the raised floor for west zone, middle floor of Case 11.

The current thermal comfort standards [14][15] suggest the maximum and minimum operative temperatures to guarantee acceptable thermal conditions. The operative temperature, defined as the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non uniform environment [15], is typically about equal to the average of the air temperature and the mean radiant temperature. Most HVAC control systems are based on measuring and controlling only air temperature, even if it is not a good enough indicator of the comfort conditions, in particular, when the mean radiant temperature is much different from the air temperature. Figure 8 plots the surface temperature profiles of the floor exposed directly to the solar radiation when there is the raised floor ($t_{rf,t\text{-}w}$) and when there is not ($t_{slab,t\text{-}wo}$). It can be deduced that the raised floor top surface temperature is subject to a higher temperature swing than the slab. Due to the lighter thermal mass of the raised floor compared to the slab, when there is incident solar radiation, not only is $t_{rf,t\text{-}w}$ higher then $t_{slab,t\text{-}wo}$, and the peak value for $t_{rf,t\text{-}w}$ is 33.9°C versus 30.5°C of $t_{slab,t\text{-}wo}$, but also the peak temperature of the raised floor occurs one hour earlier than that of the slab temperature. Figure 8 also shows the ceiling surface temperature profiles. $t_{ceiling,b\text{-}wo}$ is lower than $t_{ceiling,b\text{-}w}$, because the higher floor temperature of the case with the raised floor radiates more heat to the ceiling. The consequences of this can be seen in Figure 9. In the figure, the air and operative temperature profiles are plotted for the case with and without the raised floor. During the working hours the air temperature is controlled by the HVAC system, thus it is constantly at the setpoint value of 24°C. The operative temperature, which better represents the comfort conditions to which the occupants are exposed, varies during the working hours. In the early morning when there is no solar radiation, $t_{room,op\text{-}wo}$ is slightly higher than $t_{room,op\text{-}w}$ and from noon to evening $t_{room,op\text{-}wo}$ is roughly 1 K lower than $t_{room,op\text{-}w}$. This means that not only does the raised floor increase the zone cooling load, but it also generates a slightly less comfortable environment. If the comparison were done at the same comfort conditions based on operative temperature instead of air temperature the cooling load for the case with the raised floor would be even higher.

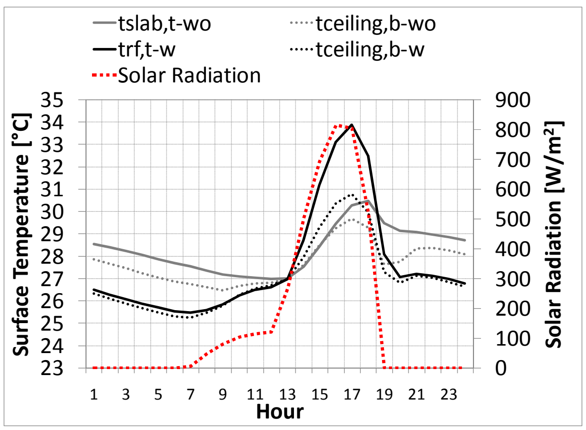


Figure 5 Floor and ceiling surface temperature profiles with and without the raised floor for west zone, middle floor of Case 11.

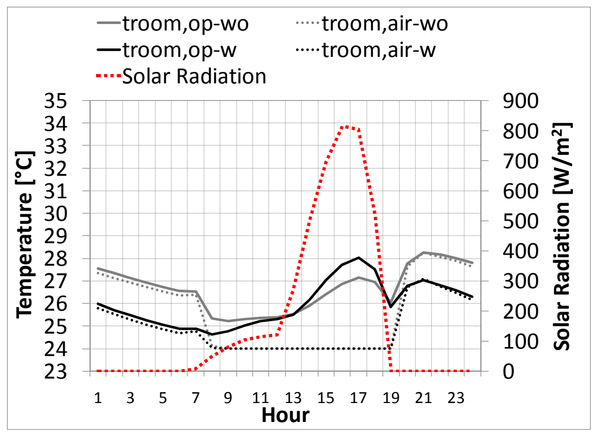


Figure 6 Air and operative temperature profiles for west zone, middle floor of Case 11 with and without the raised floor.

Significant parameters

In order to describe the different behaviour of the zone cooling load for the case with and without the raised floor the Raised Floor Cooling Load Ratio (RFCLR) is introduced and defined as the ratio of the zone design day peak hourly cooling loads calculated with and without a raised floor. RFCLR is numerically described by the following equation:

$$RFCLR = \frac{(Peak\ Cooling\ Load)_w}{(Peak\ Cooling\ Load)_{wo}} \tag{1}$$

RFCLR equal to 1 means that the zone peak cooling load for the case with and without the raised floor are the same. RFCLR greater than 1 means that the raised floor caused a zone peak cooling load greater than the case without the raised floor, e.g., RFCLR = 1.09 means that the zone peak cooling load is 9% higher in the case with the raised floor than without it. RFCLR was calculated for all the cases listed in Table 4. The Shapiro-Wilk normality test ($W = 0.84$, $p\text{-value} < 0.001$) indicates that RFCLR is not normally distributed, thus the mean and standard deviation cannot be used to describe its distribution. For all the simulated cases, RFCLR, as shown in the first box-plot in Figure 10, varied from 0.93 (minimum) to 1.4 (maximum), with a median equal to 1.05 and the first and third quartiles equal to 1.09 and 1.02, respectively. In the second and third box-plots of Figure 10, box-plots of RFCLR are shown for different floor levels (Ground Floor, Middle Floor and Top Floor) and zones (Interior, East, North, South and West). The results indicate that RFCLR is not affected by the floor level, but is influenced by the zone type. The median value for the east and west zone is equal to 1.08 and the distribution is quite wide, for the south zone it is equal to 1.06 and for the north zone 1.03. For the interior zone RFCLR is equal to 1, indicating that as expected, in the absence of direct solar radiation, the raised floor does not affect the zone peak cooling load as shown in Figure 4. Figure 11 presents the box-plots of the RFCLR calculated for all the simulated cases versus the window-to-wall ratio (20, 40, 60%), the carpet and the structure type (light-, medium- and heavy-weight). The figure shows that an increase in the WWR produces an increase of RFCLR, due to higher solar load. When the WWR increases from 20 to 60% the median increases from 1.03 to 1.07. The carpet has a strong influence on RFCLR because, if present, it reduces the ability of the slab to store the solar load. When there is no carpet the median of RFCLR is 1.09 and the distribution is quite wide. However, when carpet is present the median reduces to 1.03 with a narrow spread. Even if the zone cooling load profile is influenced by structure type the RFCLR is not strongly affected by it. For the lightweight structure the median is 1.03 and for the medium and heavyweight structure it is roughly equal to 1.06.

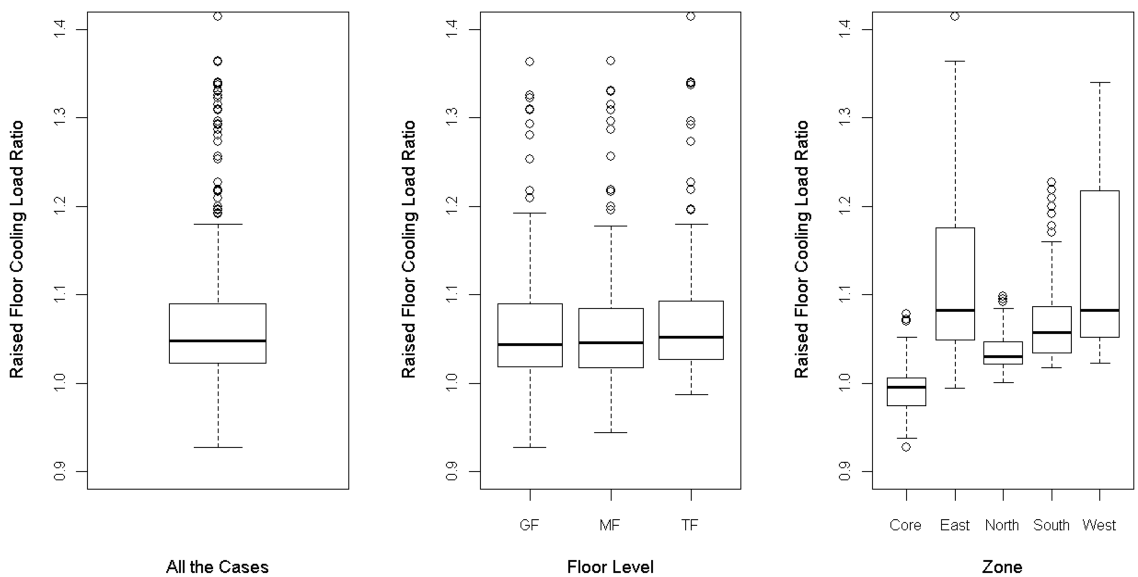


Figure 7 Box-plots of Raised Floor Cooling Load Ratio (RFCLR) calculated for all simulated cases, and versus floor level (Ground Floor, Middle Floor and Top Floor) and zone (Core (i.e. Interior), East, North, South and West).

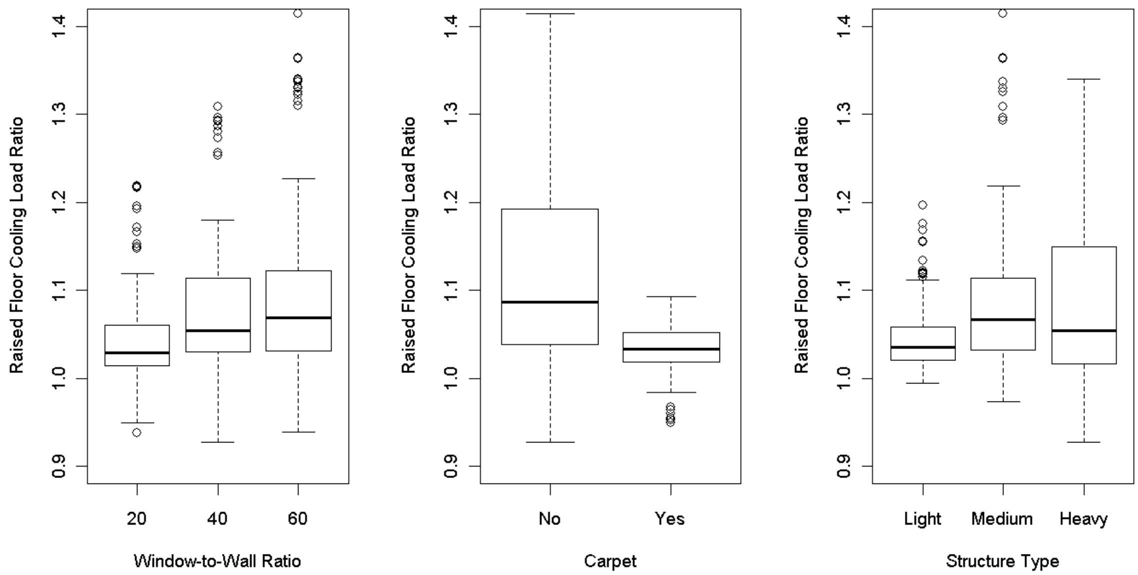


Figure 8 Box-plots of Raised Floor Cooling Load Ratio (RFCLR) calculated for all simulated cases versus window-to-wall ratio (20, 40, 60%), carpet, and structure type (light-, medium-, and heavy-weight).

A regression tree was created using the *Rpart* function in R [16] [17], the function is based on recursive partitioning. Recursive partitioning is an exploratory technique for uncovering structure in the data [18]. Regression tree strives to correctly classify members of the population based on several dichotomous dependent variables. Regression trees have the advantage to be simple to understand and interpret. Based on our analysis, the zone orientation and carpeting were identified as the two variables that largely explain the variance of RFCLR. The results are summarized in Table 7. The table shows the amount of increase in zone peak cooling load with the raised floor compared to the case without it, as a function of zone and carpeting. When carpeting is present the zone peak cooling load is between 0 and 5% higher. If there is no carpet, the zone peak cooling load is 4% higher in the north zone, 22% in the east and west zones, 12% in the south zone, and 0% in the interior zone.

Table 7 Raised Floor Cooling Load Ratio (RFCLR) obtained using a regression tree. The two variable used were the zone and the presence of the carpet.

	North	East	South	West	Interior
Without carpet	1.04	1.22	1.12	1.22	1
With carpet	1.04	1.05	1.05	1.05	1

Limitations of the study

The main limitation of this study is related to the selection of the cases to be simulated. The influence of the raised floor on the zone design cooling load profile was investigated for only one location, San Francisco, having a warm and marine climate. The size of the effect is influenced by the location and a sensitivity analysis for locations should be performed. As stated earlier, the HVAC system was not modeled, indicating that all the important issues related to the HVAC operation and interaction are not taken into account. The influence of the outdoor airflow rate for ventilation purposes on the cooling load was also not considered. The cooling load associated with ventilation may be significant (e.g., warm and humid climates). At the system level, the presence of the ventilation load may reduce the relative influence of the raised floor on the cooling load. This study has not addressed the influence of a UFAD system in which conditioned air is supplied into the plenum between the slab and the raised floor. This will be completed as part of an ongoing research project. Solar shading that may reduce this effect was not applied because it is common in the design stage to not consider internal shading for the design day calculation, and external shading is not a common technology applied in U.S. commercial buildings.

CONCLUSIONS

The main conclusions of this study are summarized below:

- The presence of a raised floor affects the zone cooling load hourly profile and the resulting zone peak cooling load. For all the simulated cases, the zone peak cooling load in the case with the raised floor varied with respect to the case without the raised floor between -7% to + 40%, with a median increase equal to 5%.
- The most significant parameters are the zone type, e.g. interior, north, west, south or east – primarily accounting for the influence of direct solar radiation, and the presence of floor carpeting. In the interior zone in the absence of solar radiation the raised floor does not affect the zone peak cooling load.
- In a building with raised flooring, the zone peak cooling load is not affected by the raised floor height.
- If carpeting is present a common interior design finish in U.S. office buildings, the overall increase in peak cooling load is reduced, ranging from 0 to 5% higher in the case with the raised floor than without it. If there is no carpet, the zone peak cooling load was 4% higher in the case with the raised floor than without it in the north zone, 22% in the east and west zones and 12% in the south zone.
- The presence of a raised floor in the perimeter zone may generate slightly less comfortable conditions due to a higher mean radiant temperature.

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NOMENCLATURE

GF	ground floor
MF	middle floor
q_{slab}	surface heat flux (W/m^2)
RFCLR	raised floor cooling load ratio
$t_{ceiling}$	top surface temperature of the slab for the cases with the raised floor (°C)
TF	top floor
t_{rf}	surface temperature of the raised floor (°C)
$t_{room,air}$	room air temperature (°C)
$t_{room,op}$	room operative temperature (°C)
t_{slab}	surface temperature of the slab (°C)
UFAD	under floor air distribution
WWR	window-wall ratio
Subscript	
b	bottom of the surface
t	top of the surface
w	cases with the raised floor
wo	cases without the raised floor

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