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Simplified calculation method for design cooling loads in Underfloor Air Distribution (UFAD) systems

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ABSTRACT

This paper describes the development of a simplified calculation method for design cooling loads in underfloor air distribution (UFAD) systems. The simplified design tool is able to account for key differences between UFAD and traditional mixing overhead (OH) systems. These include: (1) difference between design day cooling load profiles, (2) impact of a thermally stratified environment for UFAD vs. well-mixed for OH, and (3) impact of heat transfer (temperature gain) in underfloor air supply plenums. The new design tool allows the use of a familiar load calculation procedure for OH mixing systems as input to the UFAD design tool. Based on 87 EnergyPlus simulations, four regression models have been developed to transform the OH cooling load into the UFAD cooling load, and then to split this total load between the supply plenum, zone (room), and return plenum. The regression models mainly depend on floor level, and position (interior or perimeter) and orientation of the zone under analysis. Although considered in the analysis, supply air temperature, window-to-wall ratio, internal heat gain, plenum configuration, climate, presence of the carpet and structure type do not strongly influence the developed models. The results show that, generally, UFAD has a peak cooling load 19% higher than an overhead cooling load and 22% and 37% of the total zone UFAD cooling load goes to the supply plenum in the perimeter and interior, respectively.

KEYWORDS

Underfloor Air Distribution (UFAD)
Cooling load
HVAC sizing
Overhead Air Distribution (OH)
Mixing Ventilation

INTRODUCTION

Underfloor air distribution (UFAD) is a mechanical ventilation strategy in which the conditioned air is delivered to the zone from a pressurized plenum through floor mounted diffusers. UFAD has the potential to increase flexibility to change office layout and to reduce the floor-to-floor height [1]. UFAD systems may also provide improved indoor air quality [2] and thermal comfort,, as well as energy savings [1].

UFAD cooling load calculation

The most commonly used cooling load calculations are based on the assumption that a zone is well mixed, meaning its temperature is uniform throughout the zone [3]. This assumption is valid over a wide range of conditions but cannot be directly applied to stratified UFAD systems. The instantaneous cooling load is the rate at which heat energy is convected to the zone air at a given point in time. Computation of 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 mass in the zone and then later transferred by convection to the space. This process creates a time lag and dampening effect. The convective portion, on the other hand, is immediately transformed into cooling load [3]. The thermal storage effect is critical in differentiating between instantaneous heat gain for a given space and its cooling load at that moment. Accounting for the time delay is a major challenge in cooling load calculation. The sum of all space instantaneous heat gains at any given time does not necessarily (or even frequently) equal the cooling load for the space at that same time [4]. Thus, using only the heat gains and not taking into account the thermal storage effect is not a proper way to calculate the design airflow rate.

The most common cooling airflow design methods for UFAD systems [5][6][7][8] are based on the assumption that the design day peak zone cooling load profile for UFAD and a well-mixed system is the same. Schiavon et al. [9] showed that the presence of the raised floor affects the cooling load profiles, therefore it is possible that the cooling load profile of UFAD is different from the cooling load profile of a building ventilated by an overhead system (also called mixing ventilation). Moreover, the presence of stratification affects the heat exchange in the zone and this may also affect the cooling load profile. In order to accurately simulate the UFAD system, two important features should be captured by the software: heat gain into the underfloor supply plenum and the room air stratification. Based on our review of available simulation tools, EnergyPlus is one of only a few building simulation programs that can consider those two key features of UFAD simulation and has been validated based on extensive laboratory testing. It performs a full heat balance of the underfloor supply plenum and thus calculates the temperature rise of the conditioned air inside the plenum during each time-step. [10][11][12]. However, EnergyPlus is a complex software and the cost and effort related to modeling a building for the cooling load calculation using EnergyPlus is, most of time, prohibitive for HVAC designers. Therefore it is valuable for practitioners to have a simplified method that transforms the cooling load calculated for a well-mixed system into a cooling load for UFAD without the need for using EnergyPlus. The drawback to this method is imprecision of the model and limitations imposed by the range of conditions over which the model has been developed.

UFAD cooling load split

A distinguishing feature of any UFAD systems is the use of an underfloor plenum to deliver supply air through floor diffusers into the conditioned space. Cool supply air flowing through the underfloor plenum is affected by the heat transfer from both the concrete slab (in a multi-story building) and the raised floor panels. Field measurements [13] [14]and computer fluid dynamic analyses [13] showed that usually the air warms up significantly, resulting in undesirable and uncontrolled air temperature discharged at the diffusers. This phenomenon is often referred to as thermal decay.

The amount of heat entering the underfloor plenum directly influences the design cooling airflow rate. Bauman et al. [15] by an analysis of heat transfer pathways in real underfloor plenums has provided evidence that supports two widely observed thermal phenomena in UFAD systems: (1) part of the cooling load is removed in the underfloor supply plenum; and (2) temperature gain (thermal decay) in open underfloor supply plenums is often larger than expected. They estimated, based upon a simplified first-law model, that for typical multi-story building configurations (raised access floor on structural slab with or without suspended ceiling), 30-40% of the total room cooling load in the interior zone is transferred into the supply plenum and about 60-70% is removed in the zone. Based on the above mentioned results, Bauman et al. [8] developed a practical design procedure for determining the required cooling air flow rate in an interior zone of a UFAD system. In this earlier study the cooling load split was fixed, therefore it will be valuable in the current study to investigate the variability of this split due to various design and operating parameters.

The purpose of this study is to develop, by means of energy simulations with EnergyPlus, a simplified model for the transformation of the cooling load calculated for a well-mixed OH system into a cooling load for UFAD and a model for prediction of the split of the UFAD cooling load between the supply plenum, zone (room), and return plenum.

METHODS

Indexes

For sizing the zone cooling airflow rate the hourly peak design day cooling load value is commonly used. Hereafter, the term “hourly peak design day cooling load” is referred to simply as “cooling load.” Figure 1 shows the models that are needed to transform the cooling load calculated for a well mixed OH system into a UFAD cooling load and to split the UFAD cooling load into the supply plenum, the zone and the return plenum.

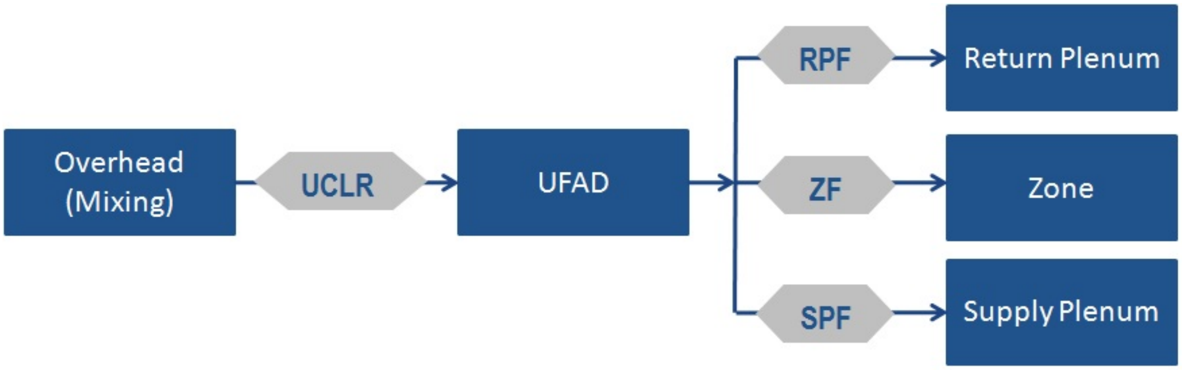

Figure 1 Schematic flow diagram of the models needed to transform the cooling load calculated for a well mixed OH system into a UFAD cooling load and to split the UFAD cooling load into the supply plenum, zone and return plenum.

The indexes reported in Figure 1 are defined below.
The UFAD Cooling Load Ratio (UCLR), defined in Equation 1, is the ratio of the cooling load calculated for UFAD to the cooling load calculated for a well mixed OH system. UCLR equals 1 means that the two cooling loads are the same. UCLR greater than 1 means that the cooling load for UFAD is higher than the cooling load for OH, for example, UCLR = 1.12 means that the UFAD cooling load is 12% higher than the OH cooling load. UCLR lower than 1 means that UFAD cooling load is lower than the OH cooling load.

$$\mathrm{UCLR} = \frac{\mathrm{CL}^{\mathrm{UFAD}}}{\mathrm{CL}^{\mathrm{OH}}} \qquad (1)$$

The cooling load for the OH system has to be calculated with standard cooling load software (e.g. based on the Heat Balance method or the RTS method [3]). The OH zone should: (a) have the same floor to floor height as the UFAD zone; (b) have no underfloor plenum; and (c)_have a return plenum that has a height equal to the sum of the UFAD supply and return plenum heights. As shown in the equations above, the plenums (both supply and return) should be modelled separately from the room spaces for both OH and UFAD systems, since the interaction between plenums and rooms turned out to be important phenomena that should be taken into account. Especially the heat gain of the conditioned air inside the underfloor plenum turned out to be very important and thus we recommend to model the plenums separately.
The Supply Plenum Fraction (SPF), defined in Equation 2, is the ratio of the cooling load removed in the supply plenum to the total UFAD cooling load. SPF may vary between 0 and 1. If, for example, SPF = 0.35 this means that 35% of the UFAD cooling load is removed in the supply plenum.

$$\mathrm{SPF} = \frac{\mathrm{CL}_{\mathrm{SP}}^{\mathrm{UFAD}}}{\mathrm{CL}^{\mathrm{UFAD}}} \qquad (2)$$

The Zone Fraction (ZF), defined in Equation 3, is the ratio of the cooling load removed in the zone (room) to the total UFAD cooling load. ZF may vary between 0 and 1. If, for example, ZF = 0.60 this means that 60% of the UFAD cooling load is removed in the zone.

$$\mathrm{ZF} = \frac{\mathrm{CL}_{\mathrm{Z}}^{\mathrm{UFAD}}}{\mathrm{CL}^{\mathrm{UFAD}}} \qquad (3)$$

The Return Plenum Fraction (RPF), defined in Equation 4, is the ratio of the cooling load removed in the return plenum to the total UFAD cooling load. RPF may vary between 0 and 1. For example, if RPF = 0.05 this means that 5% of the UFAD cooling load is removed in the return plenum.

$$\mathrm{RPF} = \frac{\mathrm{CL}_{\mathrm{RP}}^{\mathrm{UFAD}}}{\mathrm{CL}^{\mathrm{UFAD}}} \quad (4)$$

From Equations 2, 3 and 4 it can be deduced that:

$$\mathrm{CL}_{\mathrm{SP}}^{\mathrm{UFAD}} + \mathrm{CL}_{\mathrm{Z}}^{\mathrm{UFAD}} + \mathrm{CL}_{\mathrm{RP}}^{\mathrm{UFAD}} = \mathrm{CL}^{\mathrm{UFAD}}$$

and

$$\mathrm{SPF} + \mathrm{ZF} + \mathrm{RPF} = 1 \quad (5)$$

ENERGY SIMULATION

With EnergyPlus it is possible to simulate the same building with the same boundary conditions with either an overhead or a UFAD system and then, for the UFAD building, calculate for each zone the cooling load split between the supply plenum, the zone and the return plenum. To develop the models listed in the previous paragraphs a sufficiently large database has to be developed. The database development was divided in two stages. In the first, a screening of nine possible variables, listed in the section "simulated cases", affecting UCLR, SPF, ZF and RPF was performed. The most influential variables were selected and a balanced matrix (all possible combinations of the levels of the chosen independent variables) of simulations was developed. In the second stage, the results of the balance matrix were used to develop the models. In the following section, the input data for the energy simulation program is discussed [1].

Building location and weather data

In the reference case, an office building located in Baltimore, MD was modelled. The weather in Baltimore is characterized as mixed and humid according to [17]. To calculate the cooling load profile for each zone of the building, simulations were conducted for a total of 87 cases for a summer design day. ASHRAE 0.4% summer design conditions were assumed [18].

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 1858 m^2 (total floor area is 5574 m^2) and each floor is composed of 4 perimeter zones, an interior zone and a service core, which represent approximately 38%, 46% and 16% of the floor area, respectively. The floor to floor height is 3.96 m and the return plenum height is 0.6 m. The raised floor height is 0.4 m. In the building ventilated by the overhead system the raised floor is not present and the floor to floor height is equal to that served by the UFAD system. In order to maintain the same zone height, the return plenum height of the overhead building is equal to the sum of the UFAD supply and return plenums, i.e. 1 m. Strip windows are evenly distributed (i.e., a “ribbon” window) in the walls. The construction and thermal properties of the windows change in each tested climate and they comply with ASHRAE 90.1 [17]. Three building construction options are used as summarized in Table 2: light, medium and heavy weight. The effect of thermal mass is 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 in opposite directions [3]. In the building with the UFAD system there is a raised floor. Its 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 5:00 till19:00 the cooling system controls the internal air temperature to a cooling temperature setpoint of 23.9°C. The infiltration was assumed equal to 0.333 L/(s m^2) (flow per exterior surface area). The outdoor air flow rate was equal to 0.76 L/(s m^2). The outdoor air flow rate was provided from 5:00 till 19:00.

[1] The European standard 15265-2006 [16] 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.

HVAC air distribution system models for overhead and UFAD were similar. The overhead model employs variable air volume (VAV) boxes with hot water reheat coils for all zones. In the UFAD system the air is distributed through swirl diffusers in interior zones and linear bar grille diffusers in the perimeter zones. The bar grilles are ducted from the outlet side of fan coil units (FCU) served by variable speed fans. The FCU shuts off when perimeter zone temperatures are in the heating-cooling dead band, between 21.1 and 23.9°C. In cooling mode the fan is on, and in the heating mode both the fan and heating coil are on. An overhead VAV reheat system serves the service core, although no loads are assigned to this zone. Both systems are served by a single variable speed central station air handling unit (AHU) including a return air economizer, chilled water cooling coil, hot water heating coil and supply fan. A model for AHU fan control is employed to simulate a static pressure reset control strategy. The central plant consists of a central centrifugal chiller with variable speed pumps and a two-speed cooling tower. A gas fired hot water boiler provides hot water to all heating coils. Complete details of the system and plant designs can be found in [19].

Internal heat gains and occupancy

The occupants contribute to both sensible and latent heat loads in the building. The activity level of the occupants was 1.3 met (1 met = 58.15 W/m^2), and the total heat produced per occupant was thus around 140 W. The balance between sensible and latent heat is calculated by the software. Three peak occupancy levels have been studied: 22.3; 11.2 and 8.4 m^2/person). There were no people in the service core zone. In this paper, the fraction of the design value is defined as the ratio of the actual number of occupants present at their desks to the maximum number of occupants the room is designed to accommodate. The occupants' presence in the building varied according to the schedule shown in Figure 2. Three levels of internal cooling loads (people, equipments and lighting) were simulated (22.1; 40.9, 58.1 W/m^2). The equipment and lighting loads follow the schedules shown in Figure 2. Three levels of lighting loads (lighting) were simulated (10.81; 11.8, 12.9 W/m^2).

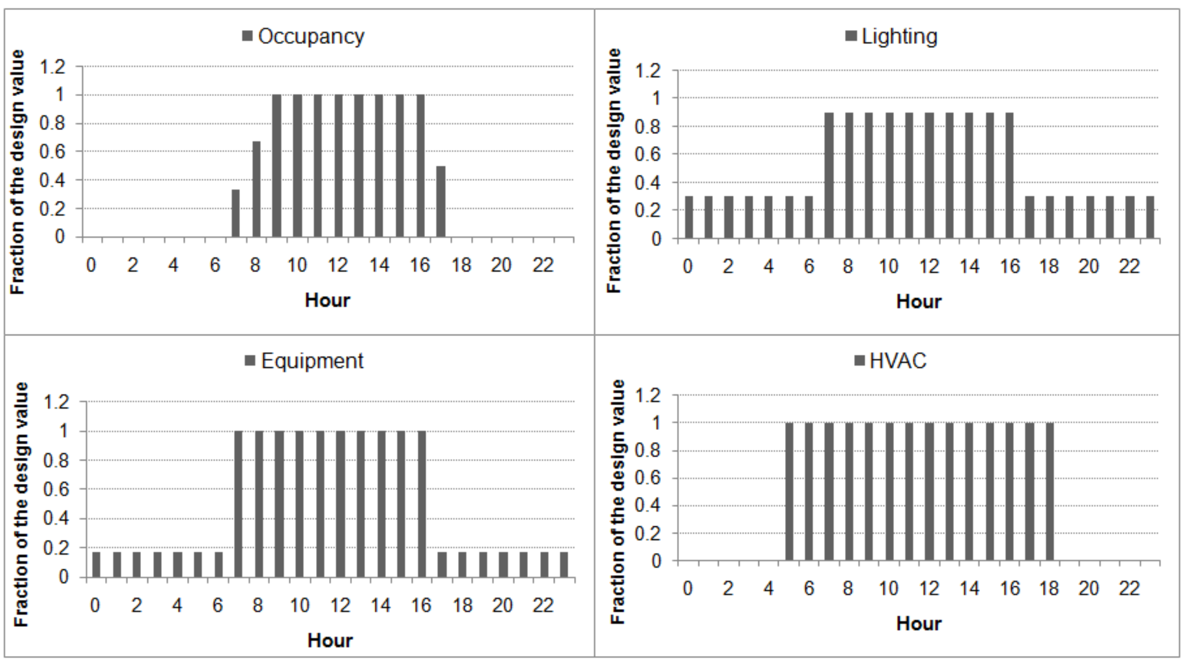

Figure 2 Occupancy, lighting, equipment and HVAC schedules.

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 by DOE [11]. 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 [3] and, to the authors' knowledge, it is one of only a few building simulation programs that have the ability to explicitly [10][11][12]. For more information about validation of the EnergyPlus program, see [20].

SIMULATED CASES

As mentioned above the work was divided into two stages. In the first one, a screening of nine possible variables affecting UCLR, SPF, ZF and RPF was performed. The most influential variables were selected and a balanced matrix (all possible combinations) of simulations was developed. In the second stage, the results of the balance matrix of simulation were used to develop the models.

Screening

To determine the most significant variables affecting UCLR, SPF, ZF and RPF, 33 simulations were performed. The influence of the following parameters was investigated: floor level, zone orientation, supply air temperature, window-to-wall ratio, internal heat gain, plenum configuration, climate, presence of the carpet and structure type. For each simulation the cooling load profile and the four indexes were calculated for the five zones (interior, east, north, west, south) of each floor level (ground, middle, top floor). The supply air temperature is the air temperature supplied to the plenum. In this model, heat gain in the supply ducts was not considered. Three levels of supply air temperature were studied: 13.9°C, 15.6°C and 17.2°C. Three window-to-wall ratios were investigated: 20%, 40% and 60%. Different WWRs are achieved by varying the window height only. Three internal gain levels were simulated. Seven different U.S. climates were investigated, which are summarized in Table 1. The influence of the carpet was also investigated. Three construction types were simulated, light-, medium-, and heavy-weight. The construction characteristics are summarized in Table 2. For the properties of the materials used, please refer to table 18 of [3]. Two plenum configurations were investigated: series (the AHU conditioned air goes from the interior to the perimeter), and parallel (the conditioned air is independently supplied to the perimeter and interior plenums).

Table 1 Climates investigated

Denomination	City	Climate according to ASHRAE 90.1	
HTX	Houston (TX)	2A	Hot and Humid
LVNV	Las Vegas (NV)	3B	Warm and Dry
SFCA	San Francisco (CA)	3C	Warm and Marine
BMD	Baltimore (MD)	4A	Mixed and Humid
SWA	Seattle (WA)	4C	Mixed and Marine
COIL	Chicago(IL)	5A	Cool and Humid
MMN	Minneapolis (MN)	6A	Cold and Humid

Table 2 Characteristics for the construction for the light-, medium-, and heavy-weight construction class, in parenthesis the overall U-factors (W/m^2K)

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 (0.49)	100 mm of lightweight concrete, ceiling air space, acoustic tile (1.45)	19 mm gypsum, 50 mm air space, 19 mm gypsum (2.59)	100 mm of lightweight concrete, ceiling air space, acoustic tile (1.45)	100 mm of lightweight concrete, ceiling air space, Heavy insulation (0.27)
Medium-weight (MW)	100 mm brick, 50 mm insulation board, 50 mm air space, 19 mm gypsum (0.47)	100 mm of heavyweight concrete, ceiling air space, acoustic tile (1.82)	19 mm gypsum, 50 mm air space, 19 mm gypsum (2.59)	100 mm of heavyweight concrete, ceiling air space, acoustic tile (1.82)	100 mm of heavyweight concrete, ceiling air space, Heavy insulation (0.28)
Heavy-weight (HW)	100 mm brick, 200 mm of heavyweight concrete, 50 mm insulation board, 50 mm air space, 19 mm gypsum (0.45)	200 mm of heavyweight concrete, ceiling air space, acoustic tile (1.66)	19 mm gypsum, 200 mm heavyweight concrete, 19 mm gypsum (2.94)	200 mm of heavyweight concrete, ceiling air space, acoustic tile (1.66)	200 mm of heavyweight concrete, ceiling air space, Heavy insulation (0.28)

Table 3 summarizes the simulated cases for the variable screening. As a reference case the following parameters were chosen: supply air temperature equal to 17.2°C, internal heat gain equal to 22.6 W/m^2, structure type light-weight, WWR equal to 40%, series plenum configuration, carpet present, and climate for Baltimore, MD. The reference case for UFAD is case 2 and for OH it is case 1.

Table 3 Simulated cases for the variable screening

Case	Ventilation system	Supply air temperature [°C]	Internal heat load [W/m^2]	Structure type	Window-to-Wall Ratio [%]	Plenum Configuration	Carpet	City
1	OH	17.2	22.6	Light	40	Series	Yes	BMD
2	UFAD	17.2	22.6	Light	40	Series	Yes	BMD
3	OH	15.6	22.6	Light	40	Series	Yes	BMD
4	UFAD	15.6	22.6	Light	40	Series	Yes	BMD
5	OH	13.9	22.6	Light	40	Series	Yes	BMD
6	UFAD	13.9	22.6	Light	40	Series	Yes	BMD
7	OH	17.2	40.9	Light	40	Series	Yes	BMD
8	UFAD	17.2	40.9	Light	40	Series	Yes	BMD
9	OH	17.2	58.1	Light	40	Series	Yes	BMD
10	UFAD	17.2	58.1	Light	40	Series	Yes	BMD
11	OH	17.2	22.6	Medium	40	Series	Yes	BMD
12	UFAD	17.2	22.6	Medium	40	Series	Yes	BMD
13	OH	17.2	22.6	Heavy	40	Series	Yes	BMD
14	UFAD	17.2	22.6	Heavy	40	Series	Yes	BMD
15	OH	17.2	22.6	Light	20	Series	Yes	BMD
16	UFAD	17.2	22.6	Light	20	Series	Yes	BMD
17	OH	17.2	22.6	Light	60	Series	Yes	BMD
18	UFAD	17.2	22.6	Light	60	Series	Yes	BMD
19	UFAD	17.2	22.6	Light	40	Parallel	Yes	BMD
20	OH	17.2	22.6	Light	40	Series	No	BMD
21	UFAD	17.2	22.6	Light	40	Series	No	BMD
22	OH	17.2	22.6	Light	40	Series	Yes	HTX
23	UFAD	17.2	22.6	Light	40	Series	Yes	HTX
24	OH	17.2	22.6	Light	40	Series	Yes	LVNV
25	UFAD	17.2	22.6	Light	40	Series	Yes	LVNV
26	OH	17.2	22.6	Light	40	Series	Yes	SFCA
27	UFAD	17.2	22.6	Light	40	Series	Yes	SFCA
28	OH	17.2	22.6	Light	40	Series	Yes	SWA
29	UFAD	17.2	22.6	Light	40	Series	Yes	SWA
30	OH	17.2	22.6	Light	40	Series	Yes	CIL
31	UFAD	17.2	22.6	Light	40	Series	Yes	CIL
32	OH	17.2	22.6	Light	40	Series	Yes	MMN
33	UFAD	17.2	22.6	Light	40	Series	Yes	MMN

Balanced matrix

From the variable screening process (see related section in the results) it was shown that the most important variables are the floor level and zone orientation The structure type, supply air temperature, and internal heat gain showed a small but not negligible influence on the indexes. A full balanced matrix of these parameters was developed and simulated. Three supply air temperatures (13.9°C, 15.6°C and 17.2°C), three structure types (light, medium, heavy), three internal heat gain levels (22.6 W/m^2, 40.9 W/m^2 , 58.1 W/m^2), two ventilation principles (UFAD and OH) were studied, therefore 3 x 3 x 3 x 2=54 simulations were carried out. The other variables were held constant at; WWR=40, Plenum Configuration = Series, Carpet = Yes, City =Baltimore, MD.

Statistical analysis

The data distributions are reported as frequency histograms and as box-plots when more than one variable is plotted. A box-plot is a way of graphically summarizing a data distribution. In a box-plot the thick 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 smaller. Points beyond those lines may be considered as outliers and they are plotted as circles in the boxplot graphs. The interquartile range is the difference between the 25th and 75th percentiles [21]. The normal distribution of the data was tested with the Shapiro-Wilk normality test [22]. Correlation between variables is reported with Spearman's rank coefficient if the variable does not have a normal distribution and with the Pearson correlation if it has a normal distribution.

Regression models were selected based on R-squared adjusted values and authors' judgment of the maximum number of useful explanatory variables. R-squared, the coefficient of determination of the regression line, is defined as the proportion of the total sample variability explained by the regression model. Adding irrelevant predictor variables to the regression equation often increase R-squared, to compensate for this, R-squared adjusted can be used. R-squared adjusted is the value of R-squared adjusted down for a higher number of variables in the model. The statistical analysis was performed with R version 2.10.1 [23].

RESULTS AND DISCUSSION

The results and discussion section is divided into two parts. After a short introduction, where an example of cooling load profiles for overhead and for UFAD is shown, the results for the screening analysis, which was used to select the variables for the balanced matrix runs, are reported. In the second part, the results of the balanced matrix and the development of the regression equations are described.

Figure 3 shows the design day cooling load profiles for overhead (mixing) and UFAD systems for the five zones of the middle floor for the reference cases (Case 1 and 2 in Table 3). The cooling load profiles for the two systems are different. The main reason for the difference between the overhead system and UFAD is the thermal behaviour of the raised floor [9]. The HVAC system is operating from 5:00 to 19:00. The amount of energy generated in the building or entering the building is the same for the two systems but the amount that the HVAC system has to remove is different because, for the OH system, part of the energy is accumulated in the slab during the day and is released at night when the system is off. In the UFAD system the presence of the raised floor reduces the ability of the slab to accumulate heat, thereby impacting the cooling load, as described by Schiavon et al. [9].

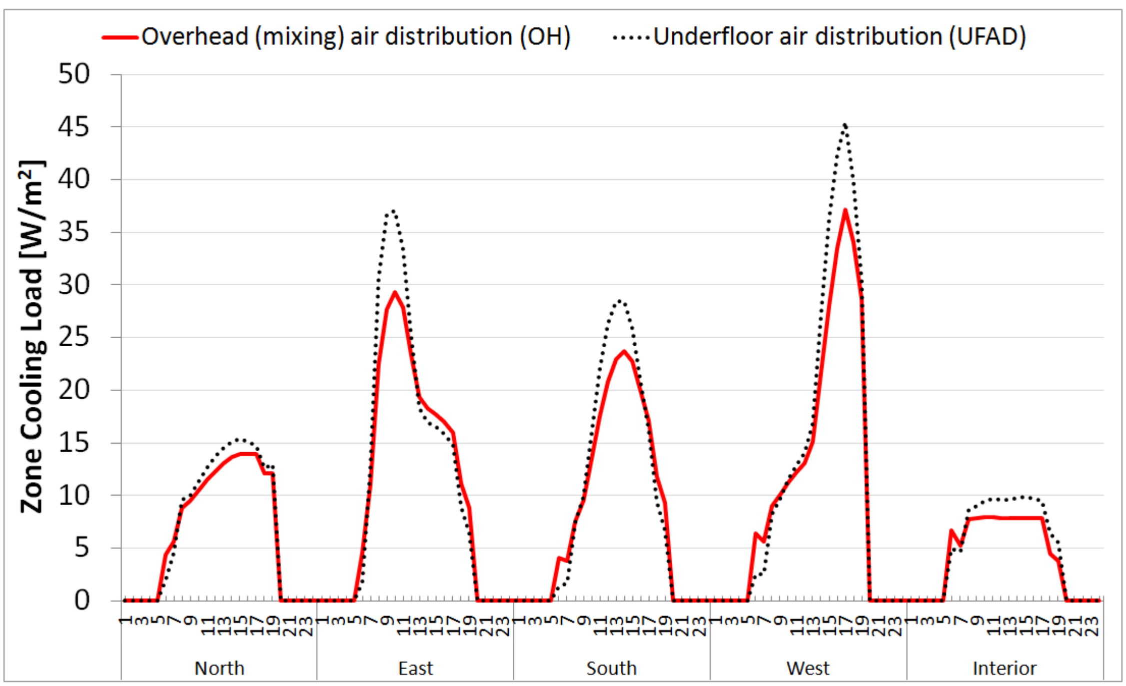

Figure 3 Cooling load profiles for overhead (mixing) and UFAD systems for the five zones of the middle floor for the Case 1 and Case 2 of Table 3.

Screening

The raw data for the screening cannot be reported here due to space limitations. They are publicly available at http://tinyurl.com/RawDataUCLR. In Figure 4 the box-plots of the UFAD Cooling Load Ratio (UCLR) for the screening simulations are shown. In the box-plots, UCLR is plotted versus supply air temperature, internal heat gain, structure type, floor level, zone, window-to-wall ratio, plenum configuration, presence of the carpet, and climate. In the same way the SPF and ZF are reported in Figure 5 and Figure 6, respectively. In all comparisons, Cases 1 and 2 of Table 3 were chosen as the reference cases.

The aim of the screening is to determine which parameters have the most significant influence on the developed indexes, and therefore should be included in the balanced matrix. From Figure 4 it can be deduced that the floor level and the zone are the parameters that mostly affect UCLR. The floor and the zone are also the parameters that mostly affect SPF (Figure 5) and ZF (Figure 6). Structure type, supply air temperature and internal heat gain slightly affect SPF. From the analysis of the RPF was deduced that the floor level is the single parameter that mostly affects RPF. From the screening it can be concluded that the most important factors are the floor level and the zone orientation. Structure type, supply air temperature, and internal heat gain have a small but not insignificant influence on the indexes. The WWR, plenum configuration, presence of the carpet and climate do not significantly affect UCLR, SPF, ZF, and RPF.

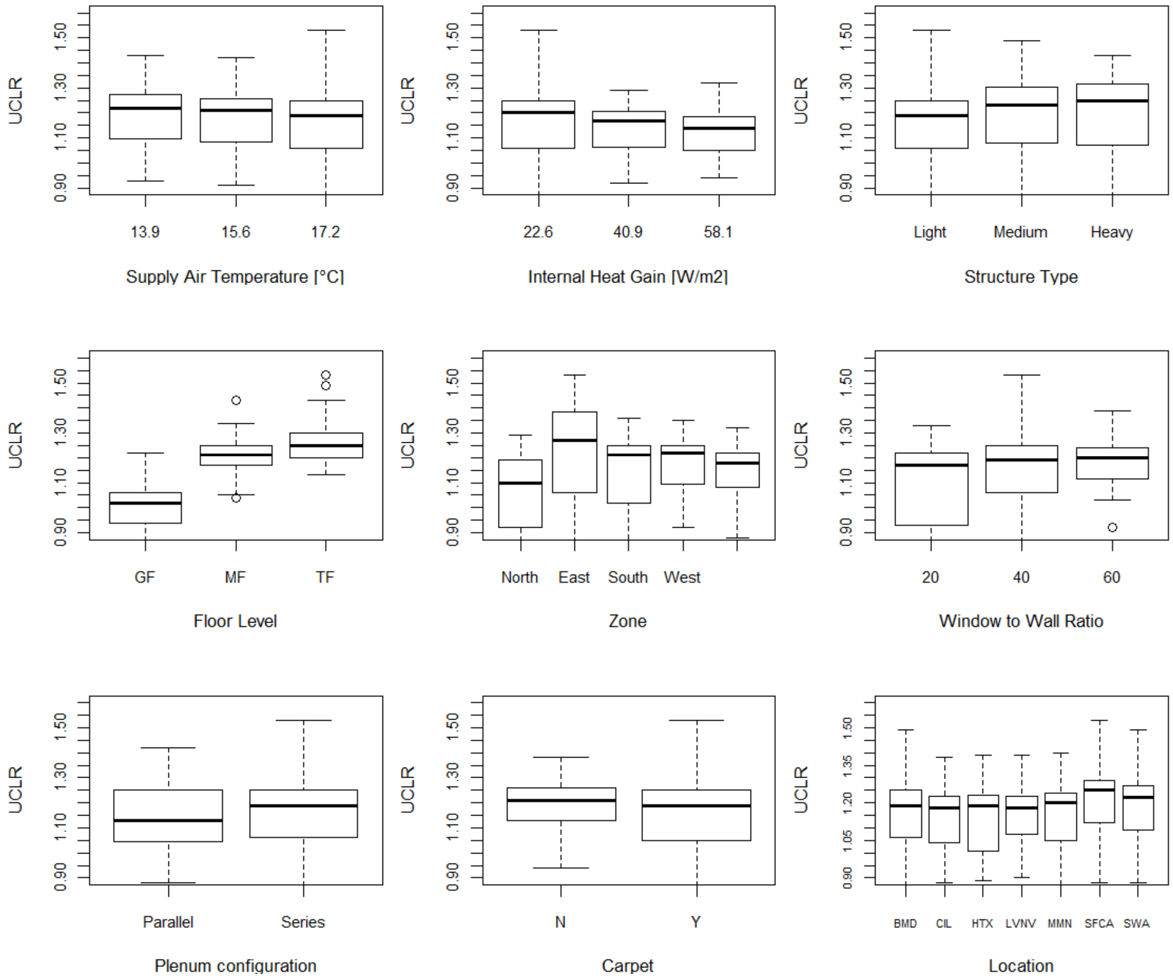

Figure 4. Box-plots of the UFAD Cooling Load Ratio (UCLR) for the screening simulations. In the box-plots UCLR is plotted versus supply air temperature, internal heat gain, structure type, floor level, zone, window-to-wall ratio, plenum configuration, presence of the carpet, and climate.

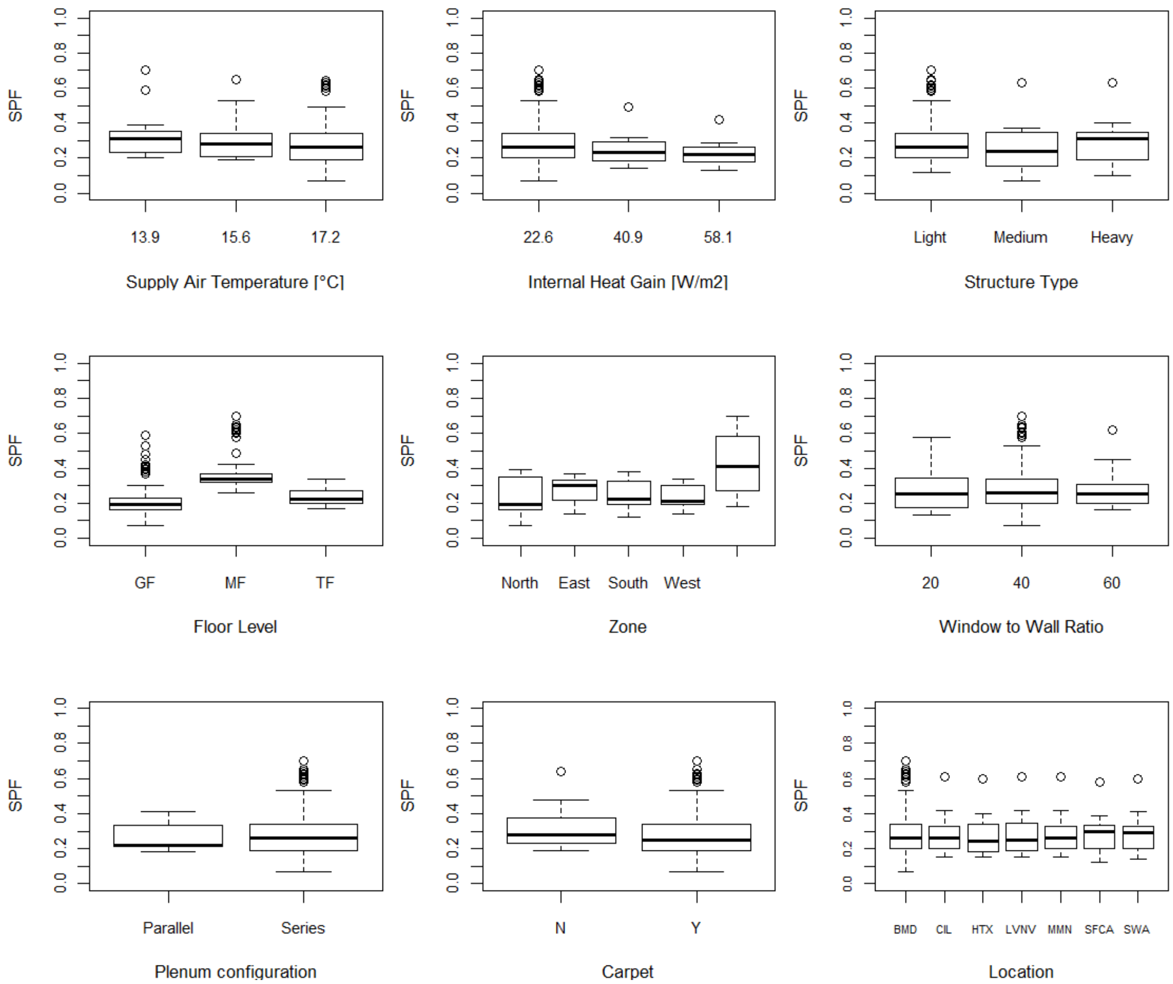

Figure 5 Box-plots of the Supply Plenum Fraction (SPF) for the screening simulations. In the box-plots SPF is plotted versus supply air temperature, internal heat gain, structure type, floor level, zone, window-to-wall ratio, plenum configuration, presence of the carpet, and climate.

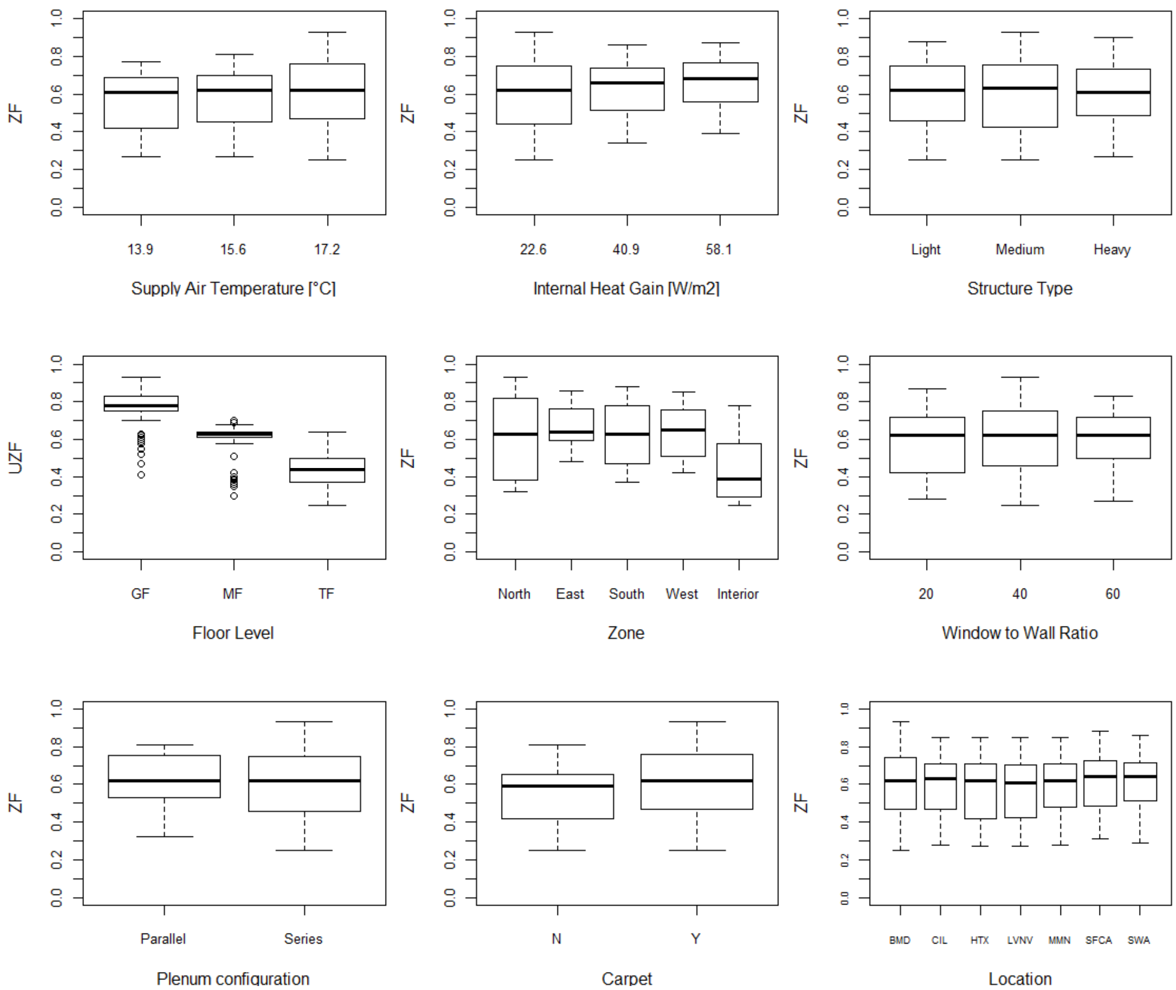

Figure 6 Box-plots of the Zone Fraction (ZF) for the screening simulations. In the box-plots ZF is plotted versus supply air temperature, internal heat gain, structure type, floor level, zone, window-to-wall ratio, plenum configuration, presence of the carpet, and climate.

Balanced matrix

The raw data are publicly available at http://tinyurl.com/RawDataUCLR. The summary statistics of all the balanced matrix simulations are reported in Table 4. UCLR has a median value equal to 1.19, this means that generally UFAD has a 19% higher peak cooling load than OH. On average, one third of the UFAD cooling load goes into the supply plenum and the other two thirds to the zone. The results are consistent with the predictions of Bauman et al. [15]. The results for RPZ are strongly skewed, i.e. the mean is different from the median. From Figure 9 it can be deduced that this is due to the fact that the value of RPF is high only in the top floor where the influence of the solar radiation to the roof affects the cooling load distribution.

Table 4 Mean, standard deviation, maximum and minimum values for the investigated parameters

Parameter	Mean	Standard Deviation	Median	Minimum	Maximum
UFAD Cooling Load Ratio (UCLR)	1.18	0.13	1.19	0.82	1.55
Supply Plenum Fraction (SPF)	0.28	0.11	0.27	0.07	0.72
Zone Fraction (ZF)	0.62	0.16	0.63	0.25	0.93
Return Plenum Fraction (RPF)	0.10	0.15	0.02	0.00	0.51

UFAD Cooling Load Ratio (UCLR)

A frequency histogram of the UCLR is shown in Figure 7. The Shapiro-Wilk normality test (W = 0.9955, p-value = 0.29) and histogram demonstrate that UCLR has a normal distribution. The correlation table (Pearson correlation coefficient - r) showed that UCLR is not correlated with the supply air temperature (r=-0.09) and only slightly correlated with the internal heat gain (r=-0.16). The box-plots of UCLR versus the independent variables (supply air temperature, internal heat gain, structure type, floor level and zone) are shown in Figure 7.

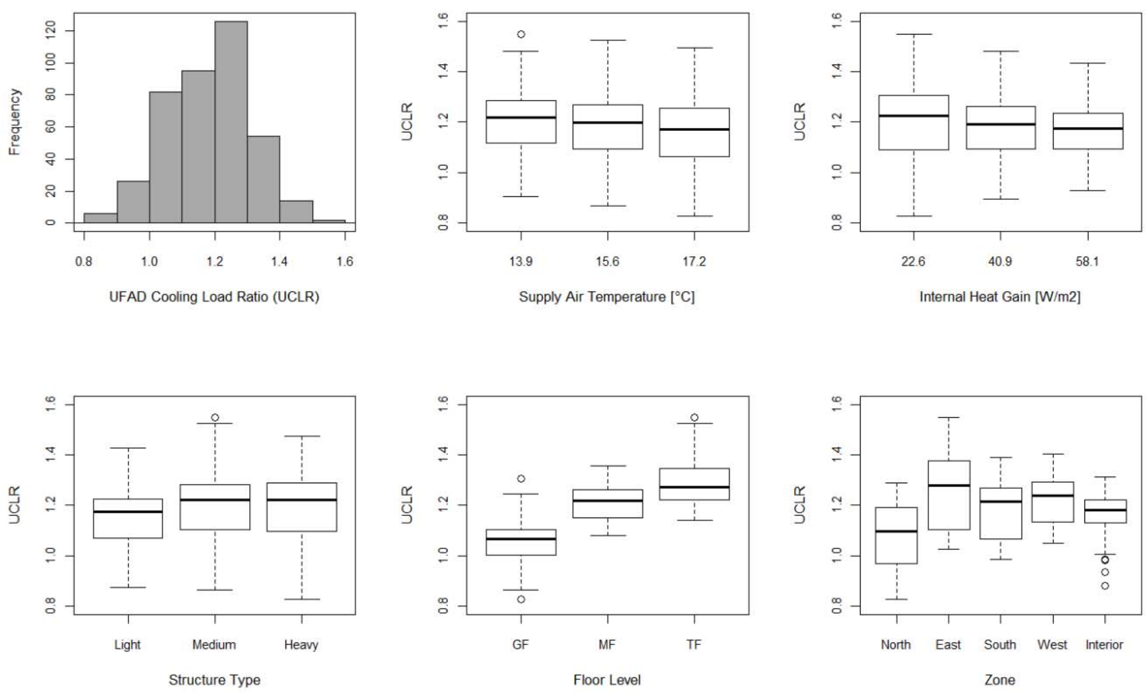

Figure 7 Frequency distribution of the UFAD Cooling Load Ratio (UCLR) and box-plots for UCLR versus supply air temperature, internal heat gain, structure type, floor level and zone.

From Figure 7 it can be deduced that the supply air temperature, internal heat gain and structure type have little effect on UCLR and thus should not be taken into account in a regression model. The floor level and zone type have a strong influence on UCLR (see Figure 7). Using these results, a multi-variable linear model was developed. The best model was selected based on the R-squared adjusted method. To keep the model as simple as possible the minimum number of explanatory variables should be used. Using all the available variables leads to an R-squared adjusted equal to 0.87. Removing the structure type, internal heat gain and the supply air temperature from the model simplifies the model without excessively reducing the value of R-squared adjusted. The interaction effects between the zone and the floor is significant ($p<0.001$) but has little influence on R-squared adjusted thus it has also been excluded. The chosen model takes into account two variables as shown in Equation 6. C_1 is a function of the floor level (ground floor, middle floor and top floor). C_2 is a function of the orientation (east, south, west, north and interior zone).

$$UCLR = C_0 + C_1 + C_2 \quad (6)$$

With:
C_0=0.9528
C_1=0 if floor is the ground floor
C_1=0.1572 if floor is between floors

C_1=0.2379 if the floor is the top floor
C_2=0 if the zone is north oriented
C_2=0.1739 if the zone is east oriented
C_2=0.0999 if the zone is south oriented
C_2=0.1349 if the zone is west oriented
C_2=0.0802 if the zone is the interior zone

From the ANOVA analysis of the multi-variable regression model was deduced that all the variables are significant ($p<0.001$) and that Adjusted R-squared is equal to 0.81. Visual evaluation of the plot of residuals versus fitted values and of the normal probability plot showed that the residuals have a normal distribution with a mean of zero and that they have the same variance for each fitted value. This means that the hypotheses of the linear regression model are met and thus, the model is valid.

Supply Plenum Fraction (SPF)
The frequency histogram of the Supply Plenum Fraction (SPF) is shown in Figure 8. The Shapiro-Wilk normality test ($W = 0.9122$, p-value < 0.001) and the histogram showed that SPF does not have a normal distribution, even if its deviation is not large. The correlation table (Spearman's rank -r) showed that SPF is very weakly correlated with the supply air temperature ($r=-0.21$) and with the internal heat gain ($r=-0.16$). The box-plots of the SPF versus the independent variables (supply air temperature, internal heat gain, structure type, floor level and zone) are also shown in Figure 8.

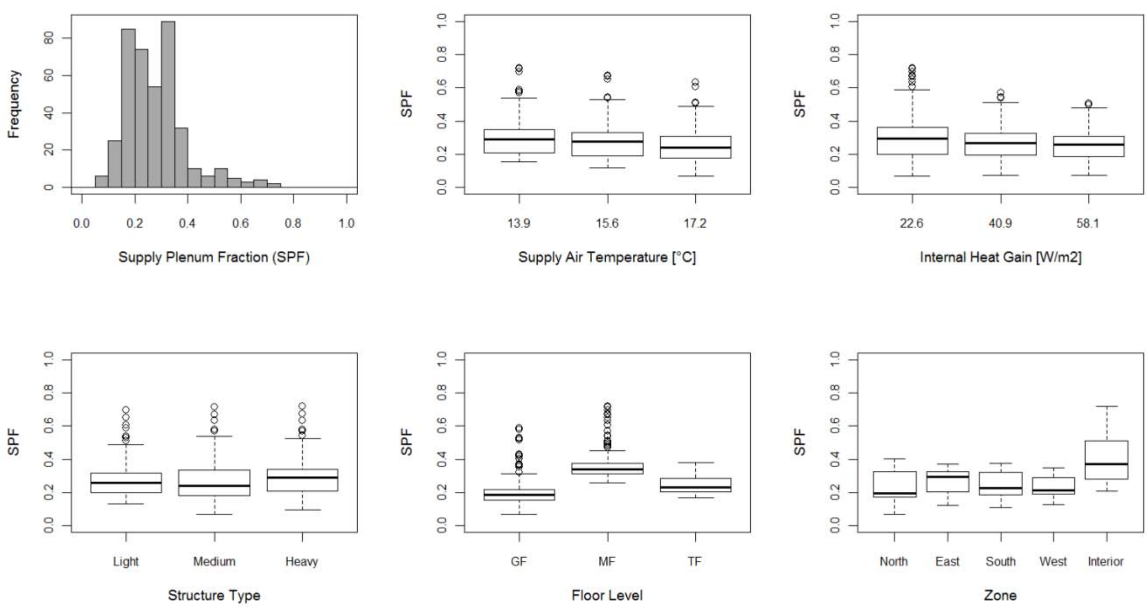

Figure 8 Frequency distribution of the UFAD Supply Plenum Fraction (SPF) and box-plots for SPF versus supply air temperature, internal heat gain, structure type, floor level and zone.

From Figure 8 it can be deduced that the zone has a strong influence on SPF; in particular there is a significant difference between interior and perimeter zones. The data was divided in two categories (interior and perimeter), the analysis showed that the perimeter zones have a median value equal to 0.22 and a narrow spread, implying that there is not much variability, the interior zone has a wider spread with a median value equal to 0.37. The narrow spread of SPF in the perimeter zone means that the perimeter zone is an effective variable explaining the amount of the cooling load going to the supply plenum and that we can expect that percentage is varying within a small range. The wide spread of SPF in the interior zone means that other factors influence SPF.

A multi-variable linear model was developed for the plenum fraction. The analysis of the R-squared adjusted values for the most significant combinations of variables showed that internal heat gain, structure type, and supply air temperature do not contribute enough to explain the variability of SPF and therefore, were not included in the model. Figure 8 shows that the influence of the four perimeter zones on SPF all behave in a similar way, therefore it is possible to lump them into a single variable called "zone lumped" that it can take only the value: interior and perimeter. The effectiveness of this new variable can also be seen by comparing the R-squared adjusted for the zone (0.35) and the zone lumped (0.33); they are almost the same, and thus, it is more convenient to use the lumped zone variable. The two-variable model (lumped zone, floor plus interaction effect) has the same R-squared adjusted as the model with all five variables. Thus, the simplest is chosen. The model has the following structure:

$$SPF = C_0 + C_1 + C_2 + C_3 \qquad (7)$$

From the ANOVA analysis of the multi-variable regression model it can be seen that all the variables are significant ($p<0.001$) and that Adjusted R-squared is equal to 0.80.

The plot of residuals vs. fitted values used to check the validity of the hypothesis of constant variance required for the linear model, showed that the hypothesis is violated (heteroscedastic). The same problem was revealed in the plot of the square root of the standardized residuals versus the fitted values. It was evident that the variability in the standardized residuals tends to increase; therefore the model was not valid. Ignoring non-constant variance when it exists invalidates all inferential tools like p-value, confidence intervals and prediction intervals [24]. To overcome the problem of non-constant variance a power transformation of the response variable (SPF) was applied. The Box-Cox method [25] was used to find the exponent of the transformation. The results showed that applying the square root the dependent variable would remove the problem. The new equations will have the following structure:

$$(SPF)^{0.5} = C_0 + C_1 + C_2 + C_3 \qquad (8)$$

With:
C_1 is a function of the zone type (interior or perimeter)
C_2 is a function of the floor level (ground floor, between floor, and top floors)
C_3 is a function of the combination of floor level and zone type
C_0=0.6179
C_1=0 if the zone is a interior zone
C_1= -0.2095 if the zone is a perimeter
C_2=0 if floor is the ground floor
C_2=0.1242 if floor is between floors
C_2=-0.0896 if the floor is the top floor
C_3=0 if the zone is interior zone or the floor is the ground floor
C_3= 0.0396 if the zone is a perimeter zone and the floor is between floors
C_3= 0.1642 if the zone is a perimeter zone and the floor is the top floor.

From the ANOVA table of the multi-variables regression model it can be seen that all the variables are significant ($p<0.001$) and that adjusted R-squared is equal to 0.79. Visual evaluation of the residuals versus the fitted values showed that the heteroscedasticity problem was solved.. A visual evaluation of the normal probability plot showed that the residuals have a mild non-normal distribution, and mild non-normality, which can safely be ignored [24]. This means that the hypotheses of the linear regression model are met and thus the model is valid.

Return Plenum Fraction (RPF)

The frequency histogram of the Return Plenum Fraction (RPF) is shown in Figure 9. The Shapiro-Wilk normality test ($W = 0.709$, p-value < 0.001) and the histogram showed that RPF has a strong non-normal distribution. The correlation table (Spearman's rank) showed that RPF is not correlated with the supply air temperature ($r=0.11$) and with the internal heat gain ($r=-0.01$). The box-plots of RPF versus the independent variables (supply air temperature, internal heat gain, structure type, floor level and zone) are also shown in Figure 9. From Figure 9 it can been seen that RPF does not vary much and the most significant parameter is the floor level. In particular, there is a clear difference between the top floor and other floors, most of the variance is generated in the top floor. The mean for the top floor is 0.30 (it has a normal distribution) and for the other floors, the median is 0.01.

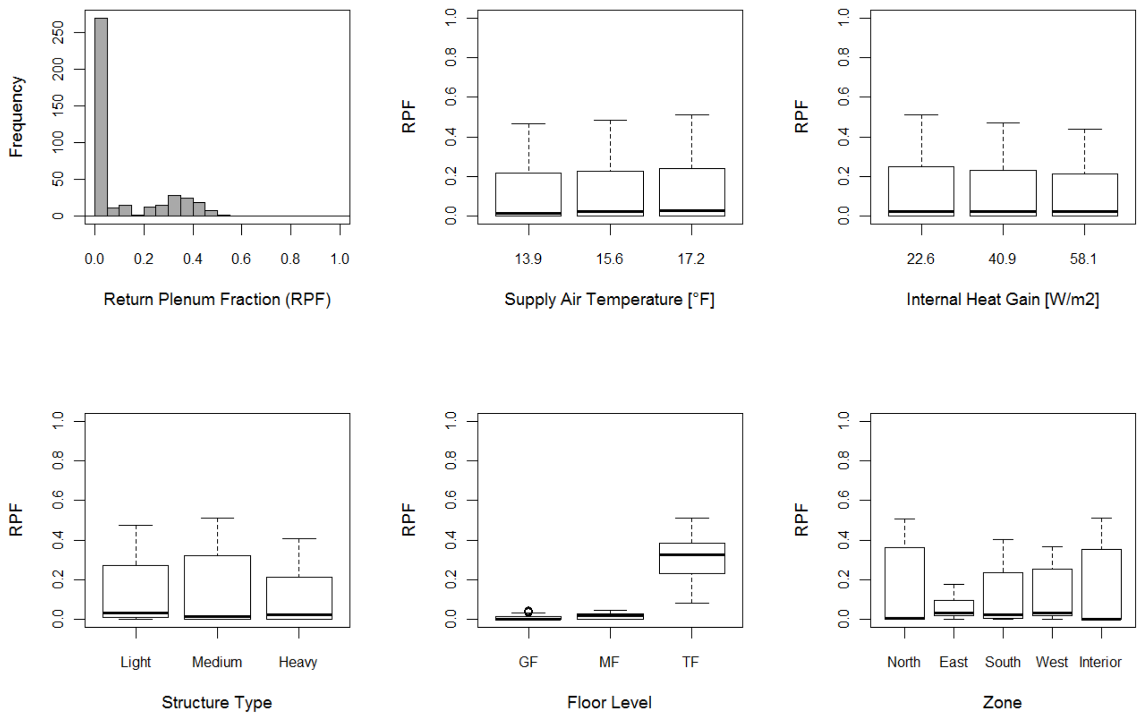

Figure 9 Frequency distribution of the UFAD Return Plenum Fraction (RPF) and box-plots for RPF versus supply air temperature, internal heat gain, structure type, floor level and zone.

The Return Plenum Fraction model is summarized in Equation 9. C_1 is a function of the floor level (ground floor, middle floor and top floor).

$$\mathrm{RPF} = \mathrm{C}_1\mathrm{X}_1 \qquad (9)$$

Where

X_1 = floor level. There are three possible levels: ground floor, middle floor and top floor.
C_1 = 0.01 if floor level is the ground floor.
C_1 = 0.01 if floor level is middle floor.
C_1 = 0.30 if the floor level is the top floor.

Zone Fraction (ZF)

The frequency histogram of the Zone Fraction (ZF) is shown in Figure 10. The Shapiro-Wilk normality test ($W = 0.971$, $p\text{-value} < 0.001$) and the histogram showed that ZF does not have a normal distribution, even if its deviation is not strong. The correlation table (Spearman's rank) showed that ZF is very weakly correlated with the supply air temperature ($r=0.10$) and with the internal heat gain ($r=0.18$). The box-plots of ZF versus the independent variables (supply air temperature, internal heat gain, structure type, floor level and zone) are also shown in Figure 10. From Figure 10 it can be deduced that the zone and floor level have the strongest influence on ZF; in particular, there is a strong influence on the interior zone. It is not necessary to develop a model for the prediction of the Zone Fraction because the sum of ZF, SPF and RPF has to be equal to 1. The models for SPF and RPF have been developed already, thus ZF=1-SPF-RPF.

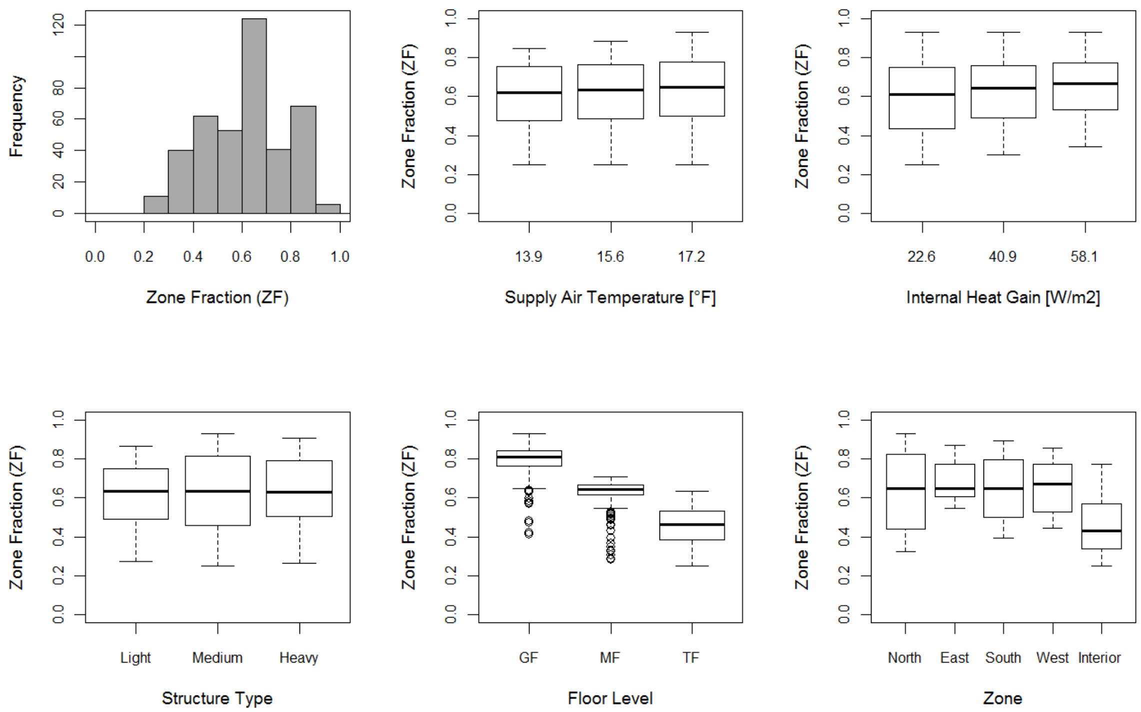

Figure 10 Frequency distribution of the UFAD Zone Fraction (ZF) and box-plots for ZF versus the supply air temperature, the internal heat gain, the structure type, the floor level and the zone.

Summary of models

In this section the developed models are summarized.

The UFAD Cooling Load Ratio (UCLR) model is summarized in Equation 10.

$$\mathrm{UCLR} = 0.9528 + \mathrm{C}_1 + \mathrm{C}_2 \quad (10)$$

Where

C_1 is a function of the floor level (ground floor, middle floor and top floor)

C_2 is a function of the orientation (east, south, west, north and interior zone)

X_1 = floor level. There are three possible levels: ground floor, middle floor and top floor.

C_1=0 if floor is the ground floor.

C_1=0.1572 if floor is between floors.

C_1=0.2379 if the floor is the top floor.

C_2=0 if the zone is north oriented

C_2=0.1739 if the zone is east oriented

C_2=0.0999 if the zone is south oriented

C_2=0.1349 if the zone is west oriented

C_2=0.0802 if the zone is the interior zone

The Supply Plenum Fraction model is summarized in Equation 11.

$$SPF = (0.6179 + C_1 + C_2 + +C_3)^2 \quad (11)$$

Where
C_1 is a function of the zone type (interior or perimeter)
C_2 is a function of the floor level (ground floor, between floor, and top floors)
C_3 is a function of the combination of floor level and zone type
C_1=0 if the zone is a interior zone
C_1= -0.2095 if the zone is a perimeter
C_2=0 if floor is the ground floor
C_2=0.1242 if floor is between floors
C_2=-0.0896 if the floor is the top floor
C_3=0 if the zone is interior zone or the floor is the ground floor
C_3= 0.0396 if the zone is a perimeter zone and the floor is between floors
C_3= 0.1642 if the zone is a perimeter zone and the floor is the top floor.

The Zone Fraction model is summarized in Equation 12.

$$\mathrm{ZF} = 1 - \mathrm{SPF} - \mathrm{RPF} \tag{12}$$

The Return Plenum Fraction model is summarized in Equation 13.

$$\mathrm{RPF} = \mathrm{C}_1 \tag{13}$$

Where

C_1 is a function of the floor level (ground floor, between floor, and top floors).
C_1 = 0.01 if floor level is the ground floor.
C_1 = 0.01 if floor level is middle floor.
C_1 = 0.30 if the floor level is the top floor.

Example
UCLR, SPF, ZF and RPF depend on the zone of the building and the floor level. In this example, UCLR, SPF, ZF and RPF have been calculated for a perimeter zone with a south orientation located in a middle floor. The calculated indices are as follows:
UCLR = 0.9528+0.1572+0.0999 = 1.21
SPF = $(0.6179-0.2095+0.1242+0.0396)^2$ = 0.337
RPF = 0.01
ZF = 1-0.337-0.01 = 0.653

Limitations of the study
The main limitations of this study are related to the selection of the cases to be simulated and to the variables investigated. The influence on UCLR, SPF, ZF, and RPF of the following variables has been evaluated: building floor level, building zone, supply air temperature, window-to-wall ratio, internal heat gain, plenum configuration, climate, presence of the carpet and structure type. We did not test the influence of the different types of raised floor construction, room height, insulation level, raised floor height and building aspect ratio. We only considered five zone orientations, i.e., other possible orientations such as south-west corner are not taken into account. Only UFAD diffuser types present in EnergyPlus were studied. The interaction with a secondary cooling system, e.g., radiant panels, was not investigated. Solar shading has not been applied because it is common in the design stage not to consider shading for the design day calculation, and external shading is not a common technology applied in U.S. commercial buildings. The roof assembly does not comply with ASHRAE 90.1 [17], lower RPF should be considered in the top floor if a better insulated roof is used. The applicability of the developed models is limited to the tested conditions.

CONCLUSIONS
The main conclusions of the development of a simplified calculation method for design cooling loads for underfloor air distribution (UFAD) systems are summarized below.

- The design day cooling load profiles for overhead and UFAD systems are different. In order to capture this difference the UFAD Cooling Load Ratio (UCLR) has been introduced. UCLR is the ratio of the cooling load calculated for UFAD to the cooling load calculated for a well mixed system (e.g., overhead). Generally, UFAD has a peak cooling load that is 19% higher than the overhead cooling load. A model to predict UCLR has been developed. UCLR mainly depends on the floor level, zone type (interior, perimeter), and orientation of the perimeter zone under analysis.

- In a UFAD system the total cooling load is divided between the supply plenum, the zone and the return plenum. Regression models to predict the split have been developed. The part of the cooling load that goes to the supply plenum mainly depends on the floor level, and the position and orientation of the zone under analysis. For all cases considered, median values of the total cooling load going to the supply plenum were found to be 22% in the perimeter zone and 37% in the interior zone. Except for the top floor the return plenum fraction is small.
- Supply air temperature, window-to-wall ratio, internal heat gain, plenum configuration, climate, presence of the carpet and structure type do not strongly influence the difference in cooling load between overhead and UFAD and the split of the cooling load between the supply air plenum, the zone and the return plenum.
- The developed regression models allow the use of a familiar load calculation procedure for mixing systems as input to the tool for the UFAD cooling load calculation.

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NOMENCLATURE

AHU	air handling unit
CL	cooling load
GF	ground floor
MF	middle floor
OH	overhead (mixing) air distribution system
Pconf	plenum configuration
RPF	return plenum fraction
SPF	supply plenum fraction
TF	top floor
UCLR	UFAD cooling load ratio
UFAD	underfloor air distribution system
WWR	window-to-wall ratio
ZF	zone fraction
Subscript	
SP	supply plenum
Z	zone
RP	return plenum

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