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Effectiveness of operable windows in office environments

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Abstract

A field study was conducted between November 2011 and March 2012 in nine modern office buildings in the Netherlands. One of the objectives was to objectify (under given weather conditions) how much control can be exercised by office workers over their indoor climate with operable windows.
To evaluate the effectiveness of the operable windows, dynamic experiments were conducted. The experiments started with the opening of windows by the research team. Next, response times and step responses were assessed in terms of air temperature changes and CO_2 concentration alterations.
For the cases studied, as far as temperature effects are concerned: the study revealed that the step response on average was -2.2 K; the average halftime value was 8 minutes; and the temperature on average changed with -0.18 K per minute after windows were opened. As far as effects on CO_2 concentrations are concerned: step response on average was -390 ppm; the average halftime value was 7 minutes; and the CO_2 concentration on average changed with -37 ppm per minute after windows were opened. An average maximum outdoor temperature of 7.9 ^oC and an average wind speed of 4 m/s were measured during the study. With some limitations, the outcomes can be used to quantify how effective operable windows can be - under non-summer conditions - to office building users that periodically want to fine-tune their indoor climate.

Keywords: personal control, adjustability, occupant behavior

Introduction

Several studies have shown that having or not having control over one's indoor climate affects how that indoor climate is perceived (Bell et al, 2002; Boerstra et al. (2013). There is growing evidence that human responses to sensory stimuli such as suboptimal temperatures modify when those exposed have control over these stimuli, i.e. when building users have adaptive opportunities (Brager & DeDear, 1998).

In this context Rohles (2007) mentions that personal preferences differ a lot, therefore the ability of an individual to control his or her environment does have a considerable effect on satisfaction with the surroundings. Bordass, Leaman & Ruyssevelt (2001) found that building occupants are most comfortable, healthy and productive in buildings that have (that perceive to have) effective operable windows and effective temperature controls. Nicol & Humphreys (1973), Paciuk (1990) & Hellwig (2015) arrived at similar conclusions.

Modern Dutch office buildings typically have several control options. Especially operable windows and adjustable thermostats are quite common. A lot is still unclear about control over indoor climate in Dutch offices and the added value of especially operable windows. An important unanswered question is: How effective are operable windows? Both in terms of thermal comfort and indoor air quality adjustability.

A field study was designed to explore the effectiveness of adjustable thermostats and operable windows in an office building context. The results related to the effectiveness of adjustable thermostats have been presented previously, see Boerstra, Loomans & Hensen (2013). In this paper the operable windows related results are presented. Here the central objective was to objectify (under given weather conditions) how much control can be exercised by office workers over their indoor climate with operable windows.

Methods

The field study was carried out in nine office buildings located in 7 different cities in the Netherlands.

The buildings were selected based on the following criteria:

- State-of-the art office work environment (relatively modern office concept);
- Well maintained building and HVAC systems;
- Gross net floor surface at least 2000 m^2 (around 22000 ft^2);
- Easy access for the research team to the workspaces (and the office workers).

The selected buildings were used by either governmental institutions or commercial organizations. The buildings were equipped with different types of HVAC systems ranging from traditional to more innovative systems such as slab heating/cooling systems.

Note that Dutch office buildings differ in an important way to average office buildings in North-America and Asia: they normally have more options for control. Eight of the nine buildings studied had operable windows and seven buildings offered possibilities for manual temperature control in winter at room level.

The buildings were visited at different times from November 2011 till March 2012. Average maximum outside temperatures during the measurement days varied from +5 to +17 °C, with one exception (in that case the daily maximum was - 3°C).

Inside the buildings relevant building and HVAC system characteristics were mapped with the use of a checklist. For example, an inventory was made of the type of heating systems installed in the buildings and of the ways these heating systems could be controlled by the building occupants. A more detailed description of the nine buildings can be found in Annex 1.

In each building several effect measurements were performed (on average 6 per building). These measurements involved temperature and CO_2 measurement that lasted half an hour or more (up to 3 hours) and that were done during and after the research team had opened a window.

The measurements allowed us to objectify the available level of control that occupants had over the indoor climate. That is, given the weather conditions at the time of measurements, the floor plans, the characteristics of the operable windows etcetera. The measurement outcomes were used to quantify the indoor climate effectiveness of the operable windows.

The window effectiveness measurement procedure consisted of 4 steps:

Step 1 'Room selection':

Upon arrival in each building a walk through survey was conducted. Indicative measurements with handheld devices of the actual room conditions (especially air temperature, relative humidity and CO_2 concentration) were used to identify suitable rooms to perform an intervention experiment in. Rooms that were not in use during the measurement day or rooms with unusual high or low (start) temperature were discarded. Selected rooms were expected not to have substantial changes in terms of heat loads and internal CO_2 production during the first 2-3 hours after the window had been opened.

Step 2. 'Start intervention':

Next the measurement equipment was installed in the selected rooms. For the measurements a calibrated Brüel & Kjær 1213 climate analyzer was used and several calibrated CaTeC klimabox 5000 logging devices. The latter allowed to log (changes in) air temperature, humidity and CO_2 concentration. The measurement equipment was placed as close as possible to one of the workstations in the room, typically at a distance of 2 to 3 m from the façade. The equipment was put at table height (around 0.7 to 0.9 m above floor level). As far as thermal comfort effects are concerned: the main focus was on (changes in) air temperature, At the start and end of each intervention (see below) control measurements (with the Brüel & Kjær 1213) were made to check for any unusual changes in radiant temperature and relative humidity during the experiment.

Step 3. 'End intervention':

At intervals of about 30 minutes, handheld devices were used to determine whether and how air temperature and CO_2 concentration had changed since t_0 (the time at which the window was opened). During these inspection rounds it was also assured that no major changes in terms of 'loading' of the rooms had taken place. As soon as a new steady state had been reached in a room the intervention was stopped (windows were closed again) (at t_{end}) after which the measurement data were retrieved for further analyses.

Step 4. 'Measurement data analysis':

Each intervention was quantified in terms of step response and response time. These terms are graphically explained in Figure 1. This is an example for temperature effect only; a similar approach is used when objectifying the CO_2 concentration effect. The step response here is defined as the difference between the measured value (air temperature in this example) at the new steady state conditions and the value at t_0. The response time is defined as the time interval between t_0 and the time t_{end} at which the new steady state has been reached. Also the concept of half-life is explained in Figure 1. Half-life ($t_{½}$) is the time interval after which the measured value (in this case air temperature) is equal to $T(t_0)$ plus 0.5·times the step response. Half-life is a general concept that is also used in other fields (chemistry, physics, biology, etc.) to describe any phenomenon which follows an exponential change in time. The prime indicator that is calculated is the indoor climate effectiveness of the windows expressed in Kelvin per minute or (in the case of the CO_2 measurements) ppm per minute. This refers to (an approximation of) the average rate at which the temperature and CO_2 concentration change during the time interval t_0 to $t_{½}$. The indoor climate effectiveness of the windows is then calculated by dividing (0.5·times the step response) (in K or ppm) with ($t_{½}$ -t_0) (in minutes).

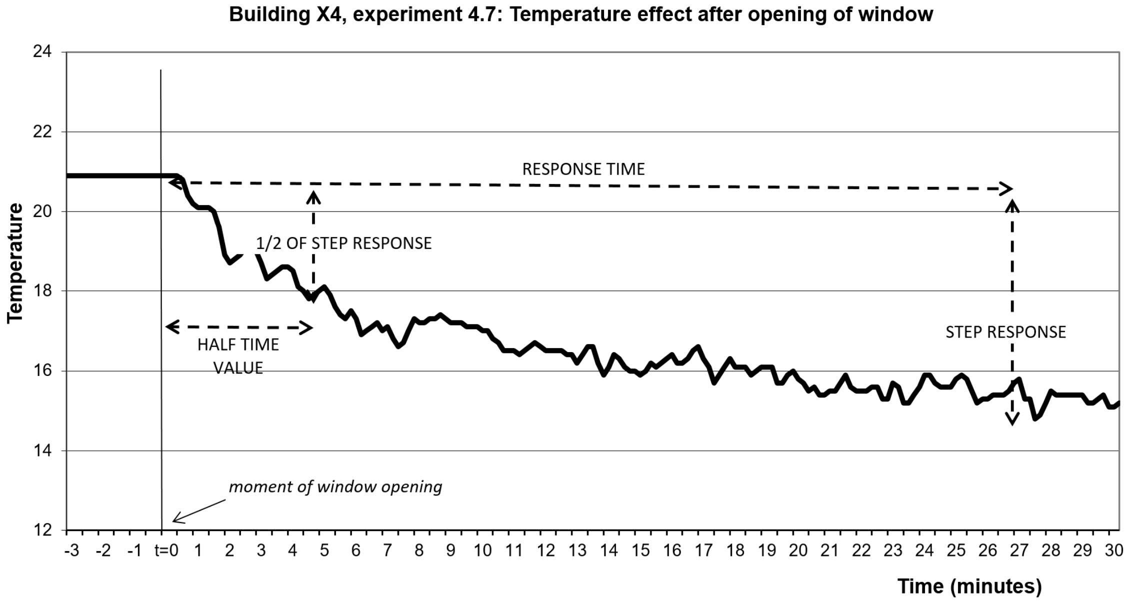
Results

Two examples of the window effectiveness measurement outcomes are presented graphically in the Figures 1 and 2. Figure 1 presents the results of a 'temperature effect experiment': an operable window was opened and the effect on air temperature was measured). Figure 2 presents the results of an 'CO_2 concentration effect experiment': an operable window was opened and the effect on CO_2 concentration was measured.

The results for all temperature measurements are summarized in Table 1. The results of all CO_2 concentration measurements are summarized in Table 2. These tables also included average weather conditions for that day.

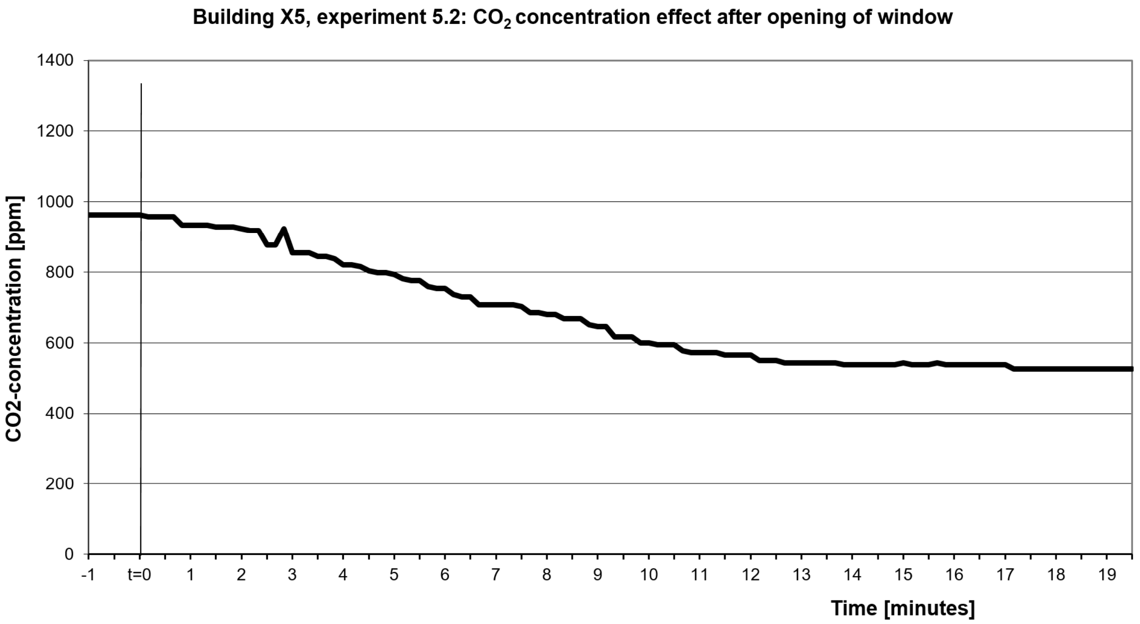
The two tables show that large differences between buildings were found. In some spaces window opening resulted in no significant effect on inside air temperature while in other buildings temperature decreases of 3 to 4 K were measured before steady state was reached. Window effectiveness in this case varied from 0 K/minute to -0.38 K/minute. The latter meaning that after windows were opened the air temperature decreased with nearly 0.4 K per minute. Note that this was measured in an office building with relatively large operable windows during rather cold outside weather. The values as obtained for the halftime value indicate for all buildings that the average response takes place within the order of minutes. That is, given the momentary outdoor conditions.

Also the CO_2 concentration measurements showed quite a bit of variation. In some spaces CO_2 concentration went down less than 100 ppm after a window was opened, in other spaces this was more than 700 ppm. Window effectiveness for CO_2 effect varied from 12 ppm/minute to more than 120 ppm /minute. The latter meaning that after windows were opened the CO_2 concentration dropped with a 'speed' of more than 120 ppm per minute. Note that this was measured in an office building with very large operable windows. Also for CO_2 concentration response times turned out to be in the order of minutes.



Date: 16-12-2011	Start time:	12:35:02	Step response: - 6.1 K	Halftime value: 5 minutes	Wind speed: 7 m/s
Space no.: A358	Floor surface: 23 m²		Response time: 27 minutes	Outside temp. (max): 4.8 °C	Wind direction: N

Figure 1. Example nr. 1 of a window effectiveness measurement outcome. During this specific experiment the focus was on air temperature effect. The figure includes an explanation of the concepts response time, step response and half-life. Note that below the figure additional information is presented such as the date of the experiment and the maximum outside temperature of that day according to the KNMI (Dutch Meteorological institute).



Date: 16-01-2012	Start time:	15:24:00	Step response: -436 ppm	Halftime value: 6 minutes	Wind speed: 4 m/s
Space no.: B2.22	Floor surface: 27 m²		Response time: 17 minutes	Outside temp. (max): 4.4 °C	Wind direction: NW

Figure 2. Example nr. 2 of a window effectiveness measurement outcome. During this experiment the focus was on CO_2 concentration effect.

Table 1. Effect of window opening on air temperature

Building	*# of experi-ments*	*AVG step response (min - max) [K]*	*AVG response time (min - max) [minutes]*	*AVG halftime value (min - max) [minutes]*	*AVG window effec-tiveness** [K/ minute]*	*Outside temp (day max) [°C]*	*Outside wind speed [m/s]*
X1	5*	-2.2 (0 ; -4.8)	38 (15 ; 85)	11 (2 ; 25)	-0.10	+17	5
X2	2*	0	-	-	0	+9	4
X3	3*	-0.1 (0 ; -0.2)	18	5	-0.01	+10	4
X4	6	-4.4 (-2.5 ; -8.7)	42 (26 ; 75)	13 (2 ; 30)	-0.17	+6	7
X5	8	-3.8 (-0.5 ; -9.6)	21 (11 ; 24)	5 (1 ; 10)	-0.38	+7	3
X6	2	-1.5 (-1.3 ; -1.6)	20 (13 ; 26)	5 (3 ; 6)	-0.15	-3	2
X7	4	-1.7 (-0.2 ; -2.5)	19 (10 ; 30)	4 (3 ; 5)	-0.21	+10	4
X8	2	-2.8 (-0.8 ; -6.8)	32 (15 ; 60)	13 (4 ; 21)	-0.11	+5	7
X9	5	-3.7 (-0.2 ; -6.2)	32 (10 ; 60)	6 (1 ; 16)	-0.31	+10	3
All combined	**37**	**-2.2**	**28**	**8**	**-0.18**	**-**	**-**

** In building X1, X2 and X3 respectively 1 time out of 5, 2 times out of 2 and 2 times out of 3 no temperature effect were measured after opening a window.*
*** Calculated with the following formula: window effectiveness = (1/2 * step response) / (halftime value)*

Discussion

The central objective was to objectify (under non-summer weather conditions) how much control can be exercised by office workers over their indoor climate with operable windows.

Due to practical circumstances it was not possible to quantify the window effectiveness in the 9 buildings under comparable weather conditions. So the outcomes cannot really be used to compare the buildings with each other. Instead the overall results should be seen as an indication of what the indoor climate effects of 'the Dutch operable office window' are when the window is opened under non-summer conditions. The halftime values as obtained indicate that the response from opening a window in any of the investigated office buildings is in the order of minutes.

The effectiveness of operable windows is not just dependent upon momentary weather conditions. Also aspects like office layout and characteristics of the operable parts have an impact. So the results of this study can only be seen as a first quantitative overview for the IEQ effectiveness of operable windows in offices. Nevertheless, with some limitations, the outcomes can be used to quantify how effective operable windows can be - under non-summer conditions - to office building users that periodically want to fine-tune their indoor climate.

Table 2. Effect of window opening on CO_2 concentration

Building	*# experiments*	*AVG step response (min - max) [ppm]*	*AVG response time (min - max) [minutes]*	*AVG halftime value (min - max) [minutes]*	*AVG window effec-tiveness [ppm/ minute]*	*Outside temp (day max) [°C]*	*Outside wind speed [m/s]*
X1	1	-190	60	5	-19	+17	5
X2	3	-310 (-70 ; -770)	52 (27 ; 90)	13 (5 ; 25)	-12	+9	4
X3*	-	-	-	-	-	+10	4
X4	2	-290 (-280 ; -300)	58 (45 ; 70)	10 (6 ; 15)	-15	+6	7
X5	2	-350 (-260 ; -440)	25 (17 ; 32)	5 (4 ; 6)	-35	+7	3
X6	2	-750 (-640 ; - 850)	26 (20 ; 31)	3 (2 ; 4)	-125	-3	2
X7	2	-450 (-370 ; -540)	26 (22 ; 29)	6 (3 ; 8)	-38	+10	4
X8	2	-380 (-220 ; -530)	23 (21 ; 24)	10 (6 ; 14)	-19	+5	7
X9*	-	-	-	-	-	+10	3
All combined	**14**	**-390**	**39**	**7**	**-37**	**-**	**-**

** No CO_2 measurements in relation to window opening effect were performed in the buildings X3 and X9*

*** Calculated with the following formula: window effectiveness = (1/2 * step response) / (halftime value)*

The results show that operable windows can be very effective and that window opening in an office building under certain circumstances can result in quite fast changes in air temperature and CO_2 concentration. The field study revealed that the temperature step response on average was -2.2 K. The average halftime value was 8 minutes and the temperature on average changed with -0.18 K per minute after windows were opened. As far as effects on CO_2 concentrations are concerned: step response on average was -390 ppm. The average CO_2 halftime value was 7 minutes; and the CO_2 concentration on average changed with -37 ppm per minute after windows were opened.

A remark concerning the air temperature effects measured: thermal comfort is not just affected by air temperature (air temperature adjustments) but also by air velocity (air velocity changes). Separate measurements have shown (not further presented in this paper) that in most of the spaces that were investigated also air velocity at work stations went up after windows were opened; often with 0.15 m/s or more. When estimating the effectiveness of the operable windows of this study in terms of overall thermal comfort adjustability one should also take air velocity effects into account and look beyond just the air temperature increases measured.

One limitation of this field study is that it was done in late autumn and winter. So the study does not offer inside in the effectiveness of operable windows (especially in terms of air temperature effects) when outside temperatures are high (20 °C and more). To estimate how the use of operable windows in summer affects indoor air temperature (thermal comfort) and CO_2 concentration, an additional study should be done during the summer months.

Another limitation is related to the definition of 'window effectiveness' that has been used in the context of this paper. For now the following formula has been used: window effectiveness = (1/2 * step response) / (halftime value). A future version of that formula also could include contextual aspects like e.g. momentary wind speed, wind direction, outside CO_2 concentration and/or outside temperature (or even better: the difference between the inside and outside CO_2 concentration / temperature at the start of the intervention).

Comparison of the results of this study to those of other field studies is not straightforward, partly because this type of study is quite rare. The authors are not aware of any other field studies that used window effectiveness measurements similar to the ones described in this paper. Haldi and Robinson (2007) studied personal control over indoor climate in eight Swiss office buildings under summer conditions, so these results could not be compared. In addition, Haldi and Robinson did not perform comparable temperature and CO_2 effect measurements as the ones described in this paper.

The operable window effects described in this paper can be compared to the adjustable thermostat effects that are described in Boerstra, Loomans & Hensen (2013). The latter were the outcomes of thermostat effectiveness measurements that were performed during the same period in the same 9 office buildings. In the best buildings (with the most effective, fastest adjustable thermostats) thermostat effectiveness at best was 0.02 to 0.03 K/minute. While temperature effectiveness for the operable windows (under non-summer conditions) turned out to be 0.18 K/minute on average. So one could state that windows were a factor 6 'faster' than adjustable thermostats. This is of course only relevant when occupants want to *lower* their room temperature. *Increasing* air temperature, during the heating season, in an office building, by opening of closing a window is not feasible.

Conclusions

The field study in the 9 office buildings showed that the average Dutch office worker can exercise a considerable amount of control over his/her indoor climate through the use of operable windows. The results imply that under non-summer conditions inside air temperature can be decreased (on average) with 0.18 K per minute. And the CO_2 concentration can be decreased (on average) with 37 ppm per minute when windows are opened. Halftime values for all investigated buildings for both parameters were, on average, less than 10 minutes.

With some limitations, the outcomes can be used to quantify how effective operable windows can be - under non-summer conditions - to office building users that periodically want to fine-tune their indoor climate.

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Annex 1. Characteristics of the nine office buildings

Aspect	**Building**				
	X1	**X2**	**X3**	**X4**	**X5**
Type of organization	Housing corporation	Main office HVAC product manufacturer	Departmental building government	Town hall	Main office construction company
Year of construction / latest major renovation	1948 / 2000	2006 / -	1967 / 1998	2003 / -	1986
Floor surface	5,000 m^2 (54,000 ft^2)	7,300 m^2 (79,000 ft^2)	33,000 m^2 (355,000 ft^2)	6,400 m^2 (69,000 ft^2)	4,100 m^2 (44,000 ft^2)
Office layout	mainly enclosed spaces, some office landscape	mainly office landscape	enclosed spaces (mainly 1, 2 and 4 person offices)	enclosed spaces (mainly 1, 2, 4 and 6 person offices)	mostly 1 person rooms
Number of floors	3	3	21	5	4
Average floor depth	25 m (82 ft)	15 m (49 ft)	23 m (75 ft)	15 m (49 ft)	13 m (42 ft)
Number of workstations	150	520	1400	220	65
Percentage of glazing	±20%	±70%	±40%	±50 & 80%	±20%
U-value glass	1.1 m^2K/W	0.7 m^2K/W	ca. 2 m^2K/W	1.6 m^2K/W	ca. 3 m^2K/W
Ventilation system	mechanical supply and exhaust system with central heat recovery (twin coil)	mechanical supply and exhaust (CAV) with heat recovery via enthalpy wheel	mechanical supply and exhaust with central recirculation	mechanical supply and exhaust (CAV), steam humidification central heat recovery via Resolair units	mechanical air supply and exhaust with heat recovery via enthalpy wheel
Heating system	after heater in above ceiling VAV induction-unit connected to district heating system	heating via 4 pipe climate ceiling connected to geothermal heating / cooling storage system and heat pump	after heater in DID induction unit connected to district heating system	radiators and convectors connected to district heating system	radiators connected to natural gas heaters
Cooling system	local cooling via VAV induction-units	local cooling via climate ceiling (see above) and central precooling of ventilation air	after cooler in DID induction unit	central precooling of the supply air	some central precooling of the supply air
Temperature control winter	wall thermostat	indirect via desktop computers connected to building management system	wall thermostat with on-off presence knob	adjustable thermostatic valves on radiators and convectors	adjustable thermostatic valves on radiator
Temperature control summer	wall thermostat	see above	wall thermostat with on-off presence knob	none	none
Ventilation control	operable windows (medium size)	operable windows (medium size)	operable window (medium)	partially operable windows (medium)	operable windows (medium, zigzag double sliding)

Annex 1. Characteristics of the nine office buildings (continued)

Aspect	Building			
	X6	**X7**	**X8**	**X9**
Type of organization	Main office façade building product manufacturer	Head quarter consumer organization (building I)	Head quarter consumer organization (building II)	Tax office government
Year of construction / latest renovation	2010 / -	1971 / 1990	1958 / 2005	2011 / -
Floor surface	2,000 m^2 (22,000 ft^2)	11,600 m^2 (125,000 ft^2)	11,200 m^2 (121,000 ft^2)	46,600 m^2 (502,000 ft^2)
Office layout	mainly office landscape	partly enclosed spaces, partly office landscape	mainly office landscape	partly enclosed spaces, partly office landscape
Number of floors	3	8	8	25
Average floor depth	16 m (52 ft)	15 m (49 ft)	15 m (49 ft)	23 m (75 ft)
Number of workstations	35	680	450	2600
Percentage of glazing	±90%	±50%	±60%	±70%
U-value glass	1.1 m^2K/W.	ca. 3.5 m^2K/W	1.2 W/m^2K	1.1 W/m^2K.
Ventilation system	air supply via double, folding façade and operable windows, mechanical exhaust in kitchen, toilet etc	natural supply via large and small operable windows, no mechanical exhaust	mechanical supply and exhaust , humidification of the ventilation air and heat recovery via twin coil	mechanical supply and exhaust system (VAV) with under floor supply
Heating system	slab heating connected to geothermal installation with heat pump	radiators connected to natural gas heaters	radiators and ventilator convectors connected to natural gas heaters and central preheating of the ventilation air	slab heating with additional convectors connected to central heat / cold storage in the soil with heat pump and central preheating of the supply air
Cooling system	slab cooling (see above)	None	ventilator convectors connected to cooling machines and central precooling of the supply air	slab cooling (see above) and central precooling of the supply air
Temperature control winter	None	adjustable non-thermostatic valves on radiators	adjustable thermostatic valves on radiators and ventilator convectors	adjustable thermostatic valves on convectors; sometimes also wall thermostats
Temperature control summer	None	None	adjustable thermostatic valves on ventilator convectors	None
Ventilation control	operable windows (large, in double folding façade)	operable windows (small and large combined)	operable windows (large)	operable windows (medium)