**FHealthy Buildings 2017 Europe**
**July 2-5, 2017, Lublin, Poland**

Paper ID: 0058 ISBN: 978-83-7947-232-1

# Effectiveness of operable windows in office environments

Atze Boerstra[1,2*], Marcel Loomans[2], Jan Hensen [2]

[1] BBA Indoor Environmental Consultancy, The Hague, The Netherlands
[2] Eindhoven University of Technology (TU/e), Eindhoven, The Netherlands

[*]*Corresponding email: ab-bba@binnenmilieu.nl*

**SUMMARY**
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. An average maximum outdoor temperature of 8 °C and an average wind speed of 4 m/s were measured during the study.
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. With some limitations, the outcomes can be used to quantify how effective operable windows can be -during the heating season- to office building users that periodically want to fine-tune their indoor climate.

**KEYWORDS**
*Personal control, adaptation, adjustability, openable windows, occupant behaviour.*

## 1 INTRODUCTION

Several studies have shown that having or not having control over one's indoor climate affects how that indoor climate is perceived (Boerstra, 2016). 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. 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.

## 2 MATERIALS/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. And 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 buildings can be found in Boerstra, 2016.

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. These 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 and $CO_2$ concentration) were used to identify suitable rooms to perform an intervention experiment in. Selected rooms were expected not to have substantial changes in heat loads and internal $CO_2$ production during the first a hour after windows were opened.

Step 2. 'Start intervention': Next the measurement equipment was installed in the selected rooms. For the measurements a calibrated Brüel & Kjær 1213 climate analyser 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 (at table height) as close as possible to one of the workstations in the room.

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) after which the measurement data were retrieved for further analyses.

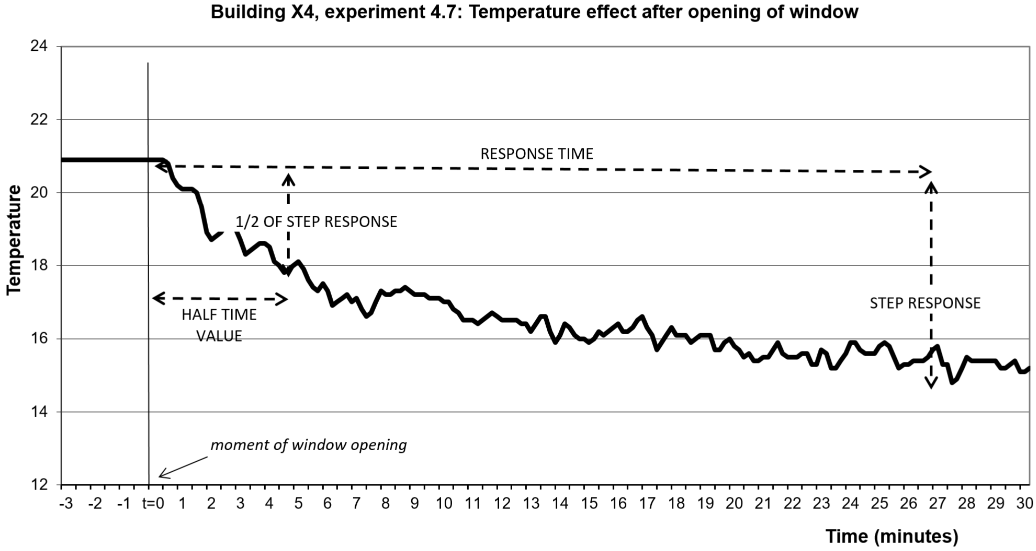
Step 4. 'Measurement data analysis': Each intervention was quantified in terms of step response and response time. These terms are graphically explained in Figure 1. The step response here is defined as the difference between the measured value (air temperature) at the new steady state conditions and 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. Half-life (t(½)) was defined as the time interval after which the measured value is equal to the value at t(0) plus 0.5 times the step response time. 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 was 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. The indoor climate effectiveness of the windows was calculated by dividing (0.5 times the step response) (K or ppm) with (t(½) – t(0)) (in minutes).

## 3 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 together are summarized in Table 1. The results of all $CO_2$ concentration measurements together are summarized in Table 2.

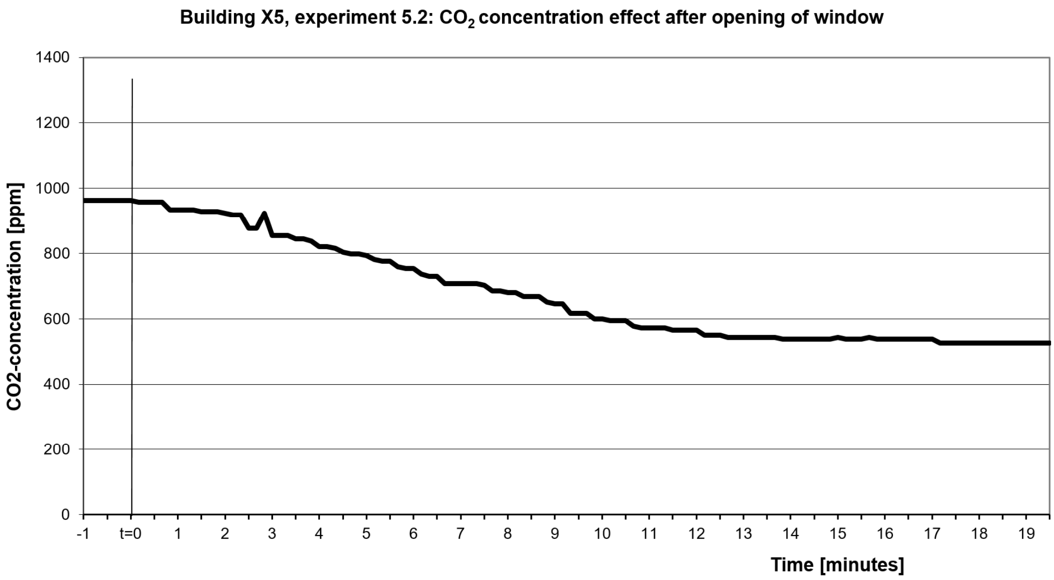
Table 1 and Table 2 communicate that large differences between buildings were found. In some spaces window opening resulted in no significant effect on inside air temperature while in other buildings temperature decreases of 3 to 4 K were measured before steady state was reached. Window effectiveness 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.




| | | | | | |
|---|---|---|---|---|---|
| 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 the effect on $CO_2$ concentration.

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 effectiveness [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 (combi) | 37 | -2.2 | 28 | 8 | -0.18 | - | - |

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

Table 2. Effect of window opening on $CO_2$ concentration

| Building | # of experi-ments | AVG step response (min - max) [ppm] | AVG response time (min - max) [minutes] | AVG halftime value (min - max) [minutes] | AVG** window effectiveness [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 (combi) | 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 formula: window effectiveness = (1/2 * step response) / (halftime value).*

## 4 DISCUSSION

The central objective was to objectify (under heating season 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 in winter. 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.

The operable window effects described in this paper can be compared to the adjustable thermostat effects that are described in Boerstra (2016). 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 turned out to be 0.18 K/minute on average. So one could state that windows in winter were a factor 6 more effective or '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.

## 5 CONCLUSIONS

The field study 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 air temperature can be decreased with a average 'speed' of 0.18 K per minute when windows are opened. For $CO_2$ concentration this is 37 ppm per minute. 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 - during heating season - to office building users that periodically want to fine-tune their indoor climate.

## 7 REFERENCES

Boerstra A.C., 2016. Personal control over indoor climate in offices. PhD thesis. Eindhoven (NL): Eindhoven University of Technology. Available via: http://repository.tue.nl/850541.

Brager, G.S. and R.J. de Dear, 1998. Thermal adaptation in the built environment: A literature review. Energy and Buildings 27(1): 83-96.

Hellwig R.T., 2015. Perceived control in indoor environments: a conceptual approach. Building Research & Information; 43(3): 302-315.

Karjalainen, S. and Koistinen, O., 2007. User problems with individual temperature control in offices. Building and Environment 2007; 42(8): 2880-2887.

Paciuk. 1990. The role of personal control of the environment in thermal comfort and satisfaction at the workplace. In: Proceedings EDRA Conference 1990, Environmental Design Research Association. Available via: www.edra.org.

Rohles, F.H., 2007. Temperature & Temperament: A Psychologist look at comfort. ASHRAE Journal, February 2007: 14-22.