# Field Study of Natural, Mechanical and Hybrid Ventilation Systems of 27 Office Buildings in the Temperate Zone country Switzerland

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## SUMMARY

Analyses in this study focus on characteristics of three different clusters of ventilation for office buildings. These comprise natural, mechanical and hybrid ventilation. In a major project study, extensive data was collected from 27 office buildings. Besides physically measurable parameters, psycho-social-oriented surveys of building users and information about building-specific constructional or building technology were compiled. In a selection, results of indoor air quality (IAQ) and indoor environment quality (IEQ) were compared with current standards. Thom's Discomfort Index (DI) suggested that, for all three clusters, populations feeling discomfort are to be expected during the summer months. Responses for certain aspects corresponding to IEQ and IAQ showed a remarkable seasonal divergence of satisfaction with air temperature for naturally ventilated buildings. The appearance of stagnant air is found to occur in its strongest form in naturally and hybrid ventilated buildings. Mechanically ventilated buildings were reported as having the lowest values for satisfaction with air humidity in winter. Each ventilation system comprises characteristic advantages and disadvantages. A tendency might favour, at least seasonally, mechanically or hybrid ventilated buildings. Differences between these two systems are not significant in this sample. The result raises the question of how much technical effort is actually necessary to provide satisfactory ventilation.

## INTRODUCTION

The field of research in how the office workers' performance, health and satisfaction are affected by conditions of the indoor environment is still up to date. Some sectors of facilities management practice endeavor to provide optimal or at least comfortable environment that can satisfy a majority of occupants. Especially in the context of commercial office environments where occupants share a common work space, satisfactory answers to the questions arising with the quality of the indoor environment (IEQ) are deemed to be important and difficult to evaluate (Kim J, de Dear R et al. 2013). These environments are characterized by restricted individual occupant's control over their surroundings. Research has shown that perceptions of indoor environment quality depend on subjective factors in addition to

environmental parameters (Kostiainen T, Welling I et al. 2008). IEQ and indoor air quality (IAQ) thermal comfort studies (Zweers T, Preller L et al. 1992; Bischof W, Bullinger-Naber M et al. 2004; Gossauer E and A 2007) usually require data analytic approaches. Statistical control for certain factors is required to evaluate possible relationships with other variables. That was found after an data analysis of data from the US BASE-study, in which multiple personal factors correlated strongly with health and comfort symptoms (Mendell MJ and Mirer AG 2009). As pointed out in the European Health Optimization Protocol for Energy-efficient buildings project (HOPE), indoor environments can have a major influence on peoples' health, well-being and comfort. The complexity of the relationships between building conditions and human well-being are shown in different studies (Bluyssen P M, Aries M et al. 2011). Sometimes effects are synergistic, and Jaakola stipulated that different determinants affect human health and comfort concurrently (Jaakola JJK 1998).
These relationships cannot be explained by average perceived indoor air quality parameters or thermal comfort responses alone. In this context it may be noted that field studies simply do not depict all the interactions or mechanisms taking place between possible sources of exposure parameters (building-related), the exposed persons (interaction-related), and the exposure parameters selected for discussing an issue (methodical approach-related). However, some relationships seem to exist between certain building characteristics and perceived comfort of office workers (Jantunen MJ, Hänninen O et al. 1998). One of the building characteristics can undoubtedly be seen in the ventilation system.

## Ventilation

There are three possible basic modes of ventilation: (a) natural ventilation, (b) mechanical ventilation and (c) hybrid (mixed-mode) ventilation. Mechanical ventilation is characterized by a fully technologically controlled operating system with a clear defined barrier between indoor and outdoor environment. In contrast, naturally and hybrid ventilated buildings are controlled by occupants, by automated systems, or a combination of both (Aggerholm S 2002). When a building's ventilation needs cannot be met naturally, hybrid ventilation would be a solution, which integrates natural ventilation and mechanical cooling. Natural ventilation, harnessed through two natural phenomena (cross-flow and buoyancy), is one of the historically conversant principles of ventilating a built environment, i.e. a building (Menassa CC, Taylor N et al. 2013). Spindler and Norford discuss that during the mode of operating natural ventilation, cool air from outside is drawn into the building to provide free cooling, thus reducing energy consumption for cooling (Spindler HC and Norford LK 2009). Most case studies consider single selected buildings as each one of these has its own technological and physical characteristic characteristics.
The aim of the present study is to compare selected IAQ parameters between office buildings fitted with different types of ventilation. The buildings are clustered according to their ventilation mode (natural, mechanical, and hybrid), and their respective systems are evaluated based on responses to occupant questionnaires. The following paragraph describes the sources of data and the approach of the major study in more detail. Data was chosen to concentrate primarily on perceived comfort with respect to the effects of ventilation.

## METHODOLOGIES

Data in this study focuses on parameters concerning IAQ and IEQ in office buildings. The underlying study focused on office buildings only. The study comprises a set of 27 office buildings, located in the regions of Zurich, Bern and St. Gallen, Switzerland. From these 27 office buildings, three buildings had natural ventilation, twelve were characterized by mechanical ventilation systems and twelve had a hybrid ventilation system, combining features of natural and mechanical ventilation. Three methods were used during the investigation in order to build up a broad information base: (a) physical parameters were measured (b) psycho-social-oriented surveys of building users were conducted regarding satisfaction, health, welfare, employment situation, mood and perceived indoor environment (Feige A, Wallbaum H et al. 2013) (c) information about building-specific constructional or building technology equipment was collected systematically from the responsible facility managers, as well as derived from an inspection of each building according to a checklist. Methods (a) and (b) were applied in a campaign of data collection both in winter and in summer. In order to make a generalized assessment for buildings, a set of measurements on selected spots (i.e. office workplaces) had to be reduced and brought up to a superior level (i.e. the whole building). In the field study context, statistical procedures for times series measurements only provide limited reliable information. A step towards considering the ‘right’ data is seen as essential to drawing comparisons between different types of buildings during phases of occupation.

## IAQ physical parameters

According to Brager and de Dear (Brager GS and de Dear R 1998), the QSB project can be assigned to a class II field study. Meeting the recommendations of the standardized EPA protocol (EPA 2003), a measurement concept has been worked out prior to data collection. The field study was conducted during a heating period (winter) and cooling period (summer) respectively. IAQ parameters of interest were climate parameters according to ISO 7730:2005 and ASHRAE standard 55-2010, which comprise climate, comfort, workplace lighting, acoustics, dust, carbon dioxide ($CO_2$), TVOC and particles. Open-plan office types were taken into account for placing the data measurement devices. IAQ measurement was performed during periods of occupancy for the winter and summer season from Tuesday to Friday. For that, nine data loggers were placed on selected working desks of workstations in each office building. Every five minutes a data point for each IAQ parameter was registered.

## Survey data collection

The questionnaire of the QSB project included questions related to personal, building and/or social aspects. Furthermore it comprised questions related to perceived comfort, which asked how one would describe typical working conditions in the office, including questions of acute health symptoms, productivity and environmental comfort. Questions were asked for summer and winter. For selected items, corresponding to IEQ and IAQ, the respondents could cross one value to assess satisfaction on certain aspects and perceived appearance of an aspect respectively.

## Data analysis and illustrations

The way in which environmental conditions are evaluated can be discussed continuously due to the large number of influencing factors in order to make meaningful indices that are representative for an entire building. Thermal comfort is a function of temperature, humidity, air-flow and window position. IAQ is also a function of temperature, air-flow and window position as well as $CO_2$ concentrations. While $CO_2$ is not necessarily a contaminant that will harm occupants in most buildings, it is often used as a tracer in industry to monitor how well a system is ventilating a space (Menassa CC, Taylor N et al. 2013). Helmis et al. showed in their study that usually the sole predominant factor of discomfort feeling is thermal comfort,

discomfort may be attributed to co-existence of unsatisfactory thermal comfort conditions and IAQ (Helmis CG, Assimakopoulos VD et al. 2009).
Collected data is analyzed for thermal comfort and IAQ in comparison to the current American standards (ASHRAE 2004; ASHRAE 2010a; ASHRAE 2010b) and to the Swiss SECO recommendations for occupants in office buildings (SECO 2011). The recommended maximum value for $CO_2$ concentration in office buildings is indicated at 1,000 ppm, according to ASHRAE Standard 55. Recommended values for relative air humidity in office buildings is indicated by 30-60%, and ranges for indoor air temperature in office buildings are indicated by 20-24°C (winter) and 23-26°C (summer), according to thermal comfort (ASHRAE 2004). Recommendations of SECO indicate 30-50% (winter) and 30-60% (summer) for humidity and 21-23 °C (winter) and 22-28°C (summer) for temperature.
Instead of qualifying PMV or PPD indices derived from the corresponding considerations (Fanger PO 1970), we wish to illustrate our data differently, in a less intertwined way. For that we chose Thom's Discomfort Index (DI), applied for indoor environment (Epstein Y and Moran DS 2006). The formula was used as follows:

$$DI = T - (0.55 - 0.0055rH) \cdot (T - 14.5) \quad (1)$$

where DI is the Discomfort Index, T is mean indoor air temperature in (degree C) and rH is the mean indoor relative air humidity of air. Thom's DI reflects the proportionate contribution of air temperature and relative air humidity on the human thermal comfort. As suggested by Giles et al. the indoor air conditions are satisfactory (means: no discomfort) when the value of the index DI is lower than 21. Values in the range from 21 to 24 are set for alarm (Giles BD, Balafoutis CH et al. 1990), where less than 50% of the population feels discomfort.
Collected data is seen sufficient with respect to the objective of investigation. Analysis was carried out graphically and statistically, and discussed in detail.

## RESULTS AND DISCUSSION

The data presented in this section is a selection out of the QSB project. Each building of the sample (N=27) operated with one out of three characteristic types of ventilation. Figure 1 assigns IAQ data to three clusters of ventilation (natural, mechanical, and hybrid). Each season and each cluster is considered separately, while season-combined data (winter and summer) is set into comparison.

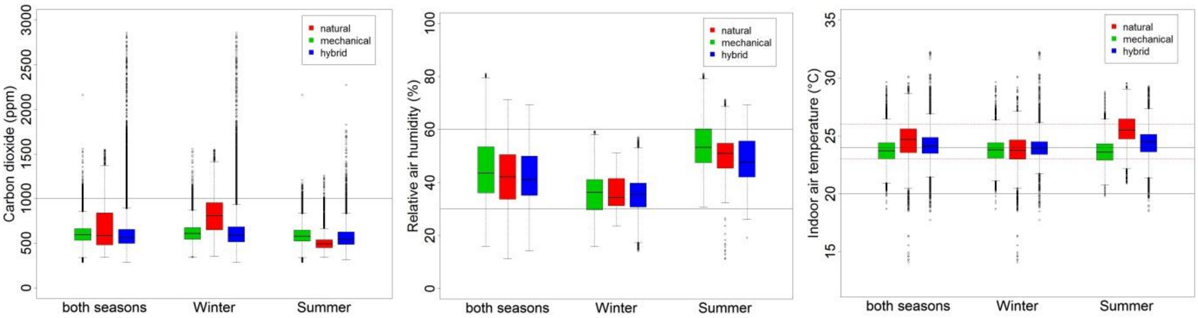



Figure 1. Seasonal differences of clusters of ventilation. IAQ parameters from left to right: Carbon dioxide, rel. air humidity and indoor air temperature.

Analyses suggest, that mechanically and hybrid ventilated office buildings provide a better air quality, especially in winter but here also observed over a two-season-period (considering winter and summer) as indicated by concentrations of $CO_2$. Tendencies towards the upper level of the recommended ranges for relative air humidity were observed for mechanically ventilated office buildings in summer. During winter, all three clusters of ventilation are characterized by tendencies towards the upper level of the recommended range for temperature. During summer, the mechanically ventilated (lowest temperature values) and the hybrid ventilated buildings (intermediate values between the recommended ranges) suggest benefits of technical facilities (for cooling) compared to naturally ventilated buildings, which show the highest temperature values (around the upper level of the recommendations).

## Questionnaire

The number of completed and returned questionnaires was 6057. A selection of the results is presented here. Questions on satisfaction with an aspect had values from *1* to *7* to be chosen from the respondents (*1* was 'not satisfactory' and *7* was 'satisfactory'). Results are shown in figure 2. Questions on perceived appearance of an aspect had values from 1 to 5 to be chosen from the respondents (*1* indicating that an unsatisfying condition appears 'permanently' and *5* indicating 'never'). Results are shown in figure 3. For the purpose of illustration, the 7-point scale and 5-point scale in figures 3 and 4 show ranges around values at 4 and 3 respectively. Cluster 1 represents 'natural ventilation', cluster 2 represents 'mechanical ventilation' and cluster 3 represents 'hybrid ventilation' for all illustrations of figure 2 and 3.

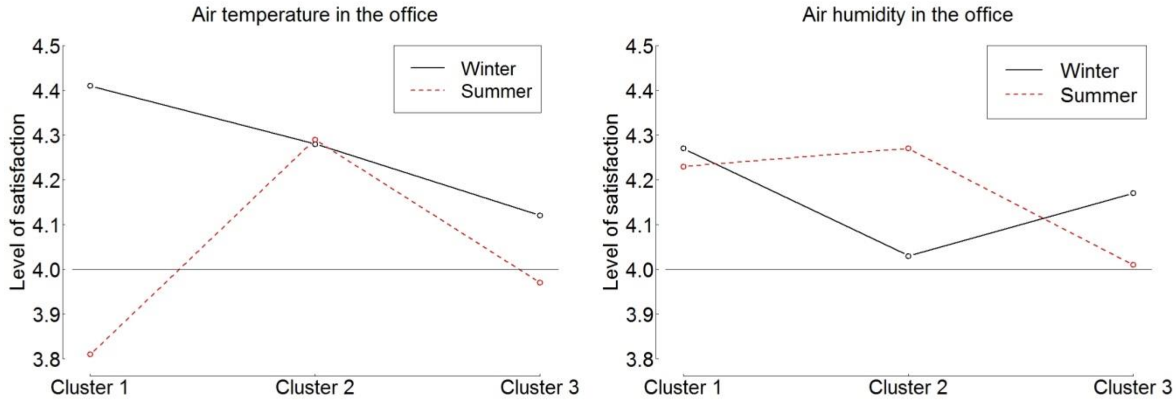
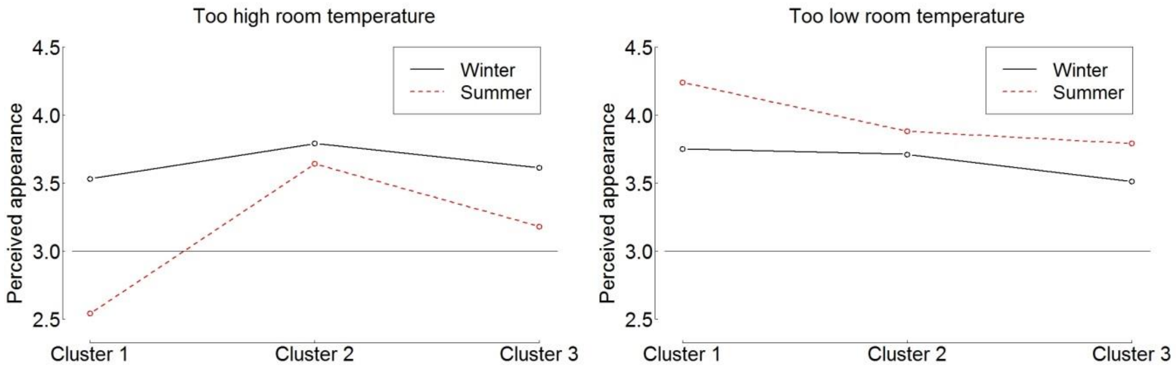



Figure 2. Responses on satisfaction for certain aspects corresponding to IEQ and IAQ.

Remarkable is a divergence of almost 0.6 value points between winter and summer when comparing satisfaction with air temperature of cluster 1. The values of cluster 2 do not differ by season, whereas cluster 3 differs by 0.15 value points. Responded satisfaction with air humidity differs slightly between winter and summer. Cluster 2 differs by 0.24 and cluster 3 by 0.16 points respectively between seasons.



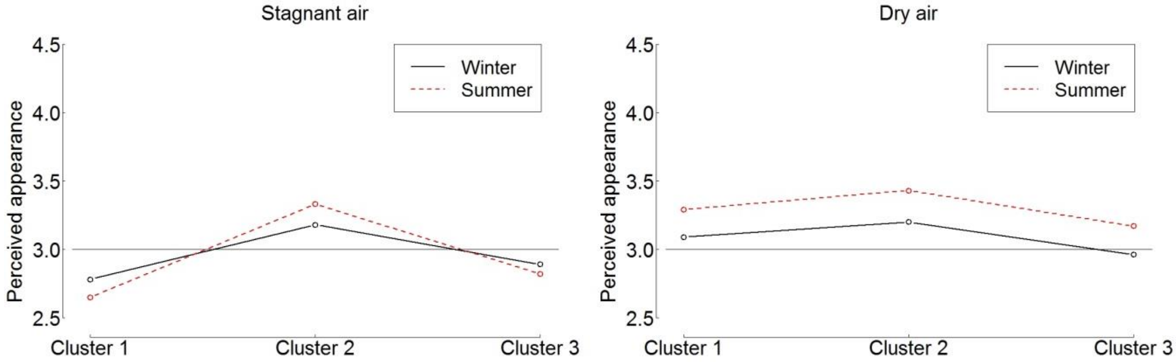



Figure 3. Responses on perceived appearance of aspects corresponding to IEQ and IAQ.

Technical benefits of mechanical or hybrid ventilation may be implied when focusing the three clusters regarding the appearance of a ‘too high room temperature’. In summer, naturally ventilated buildings show the most frequent perceived appearance (value 2.54), followed by hybrid (3.18) and mechanical ventilation (3.64). The observation for naturally ventilated buildings corresponds with the responses on the question on ‘too low room temperatures’. Perceived appearance of stagnant air is found to be prominently occurring at cluster 1 buildings with lowest values for winter and summer of 2.78 and 2.65 respectively. Perceived appearance of dry air differs constantly between winter and summer for each of the three clusters and varies only slightly between the clusters.

## Thom’s Discomfort Index

Table 1. Calculated Thom’s Discomfort Index (DI) for three clusters considering ventilation.

| | | DI Winter mean *(±sd)* | DI Summer mean *(±sd)* | Δ DI Winter - Summer | Number of buildings in cluster |
|---|---|---|---|---|---|
| All buildings (no respect to the cluster of ventilation) | | 20.51 *(±0.38)* | 21.59 (*±0.78*) | 1.08 | N=27 |
| Cluster A | ‘natural ventilation’ | 20.50 (*±0.17*) | 22.58 (*±0.34*) | 2.08 | N=3 |
| Cluster B | ‘mechanical ventilation’ | 20.44 (*±0.43*) | 21.29 (*±0.77*) | 0.85 | N=12 |
| Cluster C | ‘hybrid ventilation’ | 20.58 (*±0.38*) | 21.63 (*±0.69*) | 1.05 | N=12 |

For all clusters the mean DI in winter is lower than a value of 21, suggesting that the indoor air conditions are satisfactory and no discomfort is to be expected. For all three clusters the calculated mean DI values for summer lie in the range from 21 to 24 where less than 50% of the population feels discomfort. Remarkable are the factor 2 larger variances when comparing values between winter and summer in each of the clusters. Furthermore we can state that variances of cluster A are, at least, half the variances of cluster B and C, although delta DI of cluster A is twice the delta of cluster B and C. In this context, depending on the season, it implies that buildings with natural ventilation function more homogeneous and consistent compared to mechanical or hybrid ventilation, notwithstanding existing positive or negative effects that can be attributed to a certain type of ventilation. Yet we must consider the obviously small set of the cluster (N=3).

## CONCLUSIONS

Different aspects of evaluating IAQ and thermal comfort have been investigated with focus on the ventilation system of office buildings. Divergence was recorded in each of the three methodical approaches, between different seasons and between different clusters of ventilation. For example Thom's DI for natural ventilation showed a critical range (over 21) while questionnaire responds revealed satisfaction with air temperature in winter (not in summer) and hence provided the highest value for natural ventilated buildings. Satisfaction with air humidity showed almost no difference between winter and summer, at the same time providing the highest values out of the three clusters.

Interpretation and drawing precise conclusions is not a trivial procedure when considering all data sources. Depending on the focus of investigation, trends or principal components might be detected for identifying potential point sources causing IAQ problems related to heating, ventilation and/or air conditioning. To counter those problems at the beginning from the design stage, architects and engineers are encouraged by the total building approach, to consider building systems and their interactions with occupants.

We state that indoor climatic conditions are controlled or regulated differently in facilities, in order to provide a climate conductive as possible to the employees. Each ventilation system comprises characteristic advantages and disadvantages. Deduced from the findings presented, an overall-tendency might favour, at least seasonally, mechanically or hybrid ventilated buildings. Differences between these two systems were not significant in this sample. In summer, cooling from outside air is not only a cost-efficient strategy, but also a contribution for improving indoor climate. Hybrid ventilation systems improve the performance of the natural ventilation system of that kind that in many cases the hybrid ventilation system is capable to provide better air-quality control. As one benefit a mechanical system provides more consistent control over time, but initial cost, planning and installation as well as potential system interactions and adaptiveness are challenging. Derived from the findings the question arises of how much technical effort is actually necessary to provide satisfactory ventilation.

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