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The effect of perceived indoor air quality on productivity loss

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Abstract

This theoretical study reports on the impact of perceived indoor air quality for productivity loss in air-conditioned office buildings. A new derivation of productivity calculation model based on pollution loads and contaminant removal effectiveness is applied and the effect of the improved ventilation efficiency on productivity is estimated. The findings show that the proportion dissatisfied is a good predictor of productivity loss due to indoor air quality in different kinds of office work. It is possible to calculate the proportion dissatisfied from olf and decipol units. Productivity is possible to improve by increasing outdoor airflow rate, decreasing emissions and improving ventilation efficiency e.g. with displacement ventilation. In a case of one person per 10 m^2 (0.1 olf/m^2) and low-emitted material (0.1 olf/m^2), the total sensory pollution load is 0.2 olf/m^2. Normally, the minimum admissible outdoor airflow rate is 0.5–1.5 l/s per m^2 in office spaces. This means that 5–9% productivity loss should be accepted using the minimum airflow rate design method. With displacement ventilation, it is possible to improve indoor air quality in a manner that significantly increases productivity compared with traditional mixing system. The effect of the contaminant removal effectiveness on the productivity loss is about 0.5–2% between these systems using the same airflow rate.

Keywords: Productivity; Perceived air quality; Indoor air quality

1. Introduction

The indoor environment is where people spend 90% of their time. It is widely accepted that the indoor environmental is important for public health and that a high level of protection against adverse health effects due to inadequate quality of the indoor environment should be assured. This is incorporated in the human right to a healthy indoor environment as formulated in the WHO Constitution [1]. The human right to a healthy indoor environment includes the right to breathe clean air [2], the right to thermal comfort, and the right to visual health and visual comfort.

Fisk and Rosenfeld [3,4] have estimated in the United States that the yearly potential increase in productivity increase due to the reduction of respiratory infection cases would equal US$ 7–23 billion while a reduction of sick building syndromes (SBS) could yield around US$10–20 billion. Most significantly, improved working efficiency could yield US$ 12–125 billion. Wood [5] has determined that the salaries of workers in the US office buildings have exceeded the cost of building energy, maintenance, annualized construction and rental by a factor of 100. Skåret [6] has published a similar study in Norway and estimated that increased productivity due to an improved indoor climate is at least 10–100 times greater than the operational and maintenance costs.

In laboratory measurements, increasing the ventilation rate has been proved to be an effective method of improving the perceived quality of air polluted by human bioeffluents [7,8], tobacco smoke [9]and building materials [10]. Field studies have shown that a higher ventilation rate reduces the proportion of people dissatisfied with the perceived air quality in office buildings [11,12].

It should be noted that the ventilation system itself (air-handling unit and ductwork) could be a significant source of emissions [13]. That's why there should be the classification and inspection system for the pollution emissions to guarantee that the total emission of the system is below set targets. Experience of using a classification system to improve the total quality of the building process onward low emissions has been promising [14].

Air-conditioned office buildings are aimed to provide a acceptable indoor air quality environment for human com-

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fort and work that would in turn enable better productivity and less thermal dissatisfaction. The initial investment cost of an air-conditioning system is the usual first criterion in its system selection. This is a limited approach because it can be costly in the building economic life cycle if the air-conditioning operation and maintenance cost and the impact on office workers' productivity are not duly considered.

In a comparison between classrooms, Myhrvold et al. [15] found a significant negative association between the concentration of CO_2 (in the range <1000–4000 ppm) and the performance of pupils on three psychological tests measuring simple reaction time, choice reaction time and the colour-word test of vigilance. It may be assumed that the CO_2 concentration is a good indicator of indoor air quality in occupied rooms where bioeffluents are the most significant pollution source. This study indicates that performance monotonically decreases when ventilation rates are reduced from above 8 l/s per person down to 1 l/s per person. However, the study does not prove causation, as poor air quality may have been confounded with other negative aspects.

The results obtained by Wargocki et al. [16] in an intervention experiment indicate that reducing the pollution load on indoor air, as recommended by CEN CR 1752 [17], is an effective way of improving the perceived air quality, reducing the intensity of some sick building syndrome (SBS) symptoms and increasing some aspects of occupant productivity. In that experiment, a common pollution source was removed from a typical office space, while the ventilation rate and all other environmental parameters were kept unchanged. Lagercrantz et al. [18] repeated the same experiment with the same results. In a subsequent experiment, the outdoor airflow rate was altered at constant pollution load [19].

Eto and Mayer [20] have estimated that if minimum ventilation rates are increased from 5 l/s per person to 10 l/s per person, it is likely to change building energy use by only few percent to 10%. A cost-benefit analysis of measures to improve air quality in an existing office has been conducted [21]. Based on that study, the annual benefit due the air quality is at least 10-times higher than the energy and maintenance costs. The payback time of the improvement is less than 4 months.This theoretical study reports on the assessment of productivity loss in air-conditioned office buildings using the perceived air quality approach and makes use of Wargocki's laboratory findings [16,19] as the basis to compare and to relate how the productivity loss could be minimised through improved sensory pollution load. This interpretation using the proportion dissatisfied as a predictor of the effect on productivity indicates the nature of productivity loss that was reported in earlier studies. In this paper, a new derivation of productivity calculation model based on pollution loads and contaminant removal effectiveness is applied and the effect of the improved ventilation efficiency on productivity is estimated.

2. Comfort equation for indoor air quality

Fanger [22] introduced the olf- and decipol- units, which make it possible to quantify and compare different types of pollution sources. It should be noted that human bioeffluents are normally a less significant source of pollution than building-furnishing materials and ventilation systems. These hidden sources are believed to be the main reason for the sick building syndrome.

Olf is a unit of perceived air pollution. One olf is the emission rate of air pollutants from one standard person. Building materials emissions have been estimated at 0.1–0.2 olf/m^2. The value of 0.1 olf/m^2 floor area presents a low-polluting building. If no selection of material takes place, the building is characterized as non-low-polluting, with a sensory pollution load of 0.2 olf/m^2 floor area or more [16].

The decipol unit quantifies the level of perceived air quality. Humans perceive air quality by their olfactory and chemical sense, being sensitive to odorants and irritants in the air. One decipol is the pollution caused by one standard person (one olf) ventilated by 10 l/s of fresh outdoor air.

Fanger [22] has published the equation to estimate the number of the dissatisfied as a function of the perceived air pollution using the decipol unit. Eq. (1) shows the correlation between the percentage of dissatisfied and the decipol level.

$$PD = 395\mathrm{e}^{(-3.25 \cdot C^{-0.25})} \quad (1)$$

where PD = percentage of dissatisfied; C = perceived air quality, decipol.

People are quite sensitive to the sensory pollution load and the number of dissatisfied increases rapidly at higher decipol values. Using the Eq. (1) yields the following results: one person in a low-polluting building (10 m^2 per person) with 10 l/s per person means 24% dissatisfied. If the level is 1.4 decipol, the percentage dissatisfied is 20% and at 2.5 decipol 30%. All this means that to maintain the number of the dissatisfied people at acceptable level, the material and system pollution must be minimized at a reasonable outdoor airflow rate.

It should be noted that in practice the perceived indoor quality is better because of infiltration and ventilation effectives. Normally, the infiltration is 0.1–0.3 1/h (0.07–0.2 l/s per m^2 with 2.5 m free ceiling height). In the basic approach [22], it is assumed to have complete mixing. With the complete mixing system, the maximum value of the contaminant removal effectiveness is 100%. With the displacement system, it is possible to reach better contaminant removal effectiveness like 150–200% [23]. This means that displacement ventilation can improve indoor environment in a manner that significantly increases health and productivity.

Also if the return air is used, the human bioeffluent loads are lower because normally the ratio of occupants is typically about 65% of the design value. Anyhow, in the return-air systems the air-conditioning system e.g. return ductwork and filter could be one extra pollution source, which affects IAQ in the room spaces [13,24].

3. Perceived air quality and productivity

The results of three independent studies show that the performance of simulated office work improves when air quality increases [16,18,25]. To simulate office work, text typing, proof-reading and addition were used, all being typical office tasks. Air quality was altered either by decreasing the pollution load or by increasing the outdoor air supply rate while the pollution load was constant. In all three studies similar procedures were used: the subjects performed simulated office work during 4.5 h exposures to different air quality levels and assessed the perceived air quality.

A positive correlation was found between the acceptability of air quality and performance. The result indicate that every 10% decrease in the proportion dissatisfied with the air quality below the air quality level causing 70% to be dissatisfied can improve the performance of typing by 1.4%, of addition by 1.1% and of proof-reading by 2.3%. Thus, the productivity loss is strongly dependant on the nature of the task.

The following approach makes use of two main tasks: (1) typing of 1.4% per 10% of dissatisfied and (2) proof-reading of 2.3% per 10% of dissatisfied as a "thinking" type of task. This makes it possible to predict IAQ effects on different job descriptions by using time weighting factors for each task.

These published findings provide the impetus to create a model to estimate the impact of perceived air quality on the productivity loss of workers in an office space. Results from Wargocki [25] are, therefore, used in this study to create a generic productivity loss model using the proportion dissatisfied as a predictor. In that model, the effect of the contaminant removal effectiveness is also integrated.

Fig. 1 shows the linear correlation between perceived air quality and productivity loss. The nature of the task is a key element for productivity loss.

Using Eq. (1), it is possible to calculate that the minimum proportion dissatisfied in normal design conditions (one person/10 m^2, 10 l/s per person and low-emitted material (1 olf)) is over 26%. The productivity loss for thinking with 26% dissatisfied is 5.9% and for typing is 3.6%.

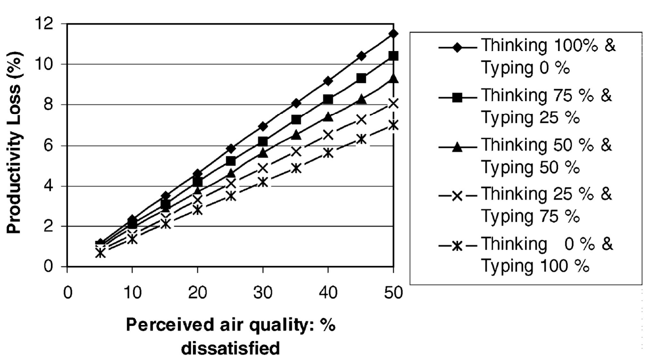

Fig. 1. Productivity loss for different combination of tasks as a function of the percent of the dissatisfied with the air quality.

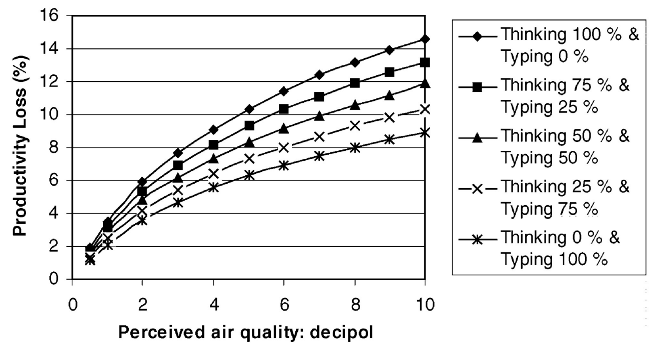

Fig. 2. Productivity loss for different combinations of tasks as a function of perceived air quality using decipol unit.

Another approach to perceived air quality is via the decipol unit (see Eq. (1)) which combines a known pollutant load (olf) and outdoor airflow rate. Fig. 2 shows the non-linear relationship between decipol and productivity.

With the quite typical decipol value of 4 (40% dissatisfied) with 2 person/10 m^2, 5 l/s per person and material emission of 0.2 olf/m^2, the productivity loss is 9.1% in the thinking and 5.6% in typing tasks.

4. Pollution load and its impact on productivity

Fanger [22] has published an equation to calculate the proportion dissatisfied with known outdoor airflow rate and pollution load. For this method is possible to add some new parameters (infiltration and ventilation efficiency) to get more generic view of the perceived air quality. Infiltration is normally 0.1–0.3 1/h (0.07–0.2 l/s per m^2 floor area) and contaminant removal effectiveness is 100% with mixing ventilation and 150–200% with displacement ventilation. Perceived air quality and productivity may be estimated from the following parameters:

- Occupant density: typically 0.05–0.75 person/m^2 [26] which means pollution load of persons 0.05–0.75 olf/m^2 floor area.
- Outdoor airflow rate: typically 0.5–6 l/s per m^2 floor area [26].
- Infiltration: typically 0.07–0.2 l/s per m^2 floor area.
- Material and ventilation system emissions: typically 0.1–0.2 olf/m^2 floor area [16].
- Contaminant removal effectiveness in the occupied zone: typical range from 100 to 200% depending on used system [23].

The outdoor airflow rate and the pollution load are the most important factors, having the greatest impact on perceived air quality.

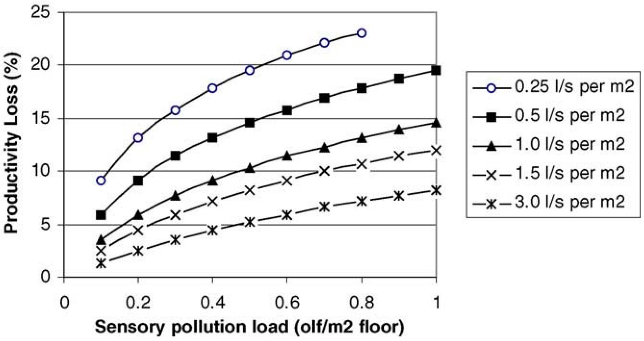

Fig. 3. Productivity loss as a function of sensory pollution load with different outdoor air supply rates in a thinking task.

Fig. 3 shows productivity loss as a function of the sensory pollution load and outdoor airflow rate in a thinking task. In Fig. 3, the infiltration was assumed to be non-existent and the contaminant and removal effectiveness to be perfect (100%).

In a case of one person per 10 m^2 (0.1 olf/m^2) and low-emitted material (0.1 olf/m^2), the total sensory pollution load is 0.2 olf/m^2. Based on the most of international building codes, the minimum admissible outdoor airflow rate is 0.5–1.5 l/s per m^2 in office spaces. This means that 5–9% productivity loss should be accepted using the minimum airflow rate design method. In a case of two persons per10 m^2 (0.2 olf/m^2) and material emission of 0.2 olf/m^2, the total sensory pollution load will be 0.4 olf/m^2. This leads to 7–13% productivity loss with the minimum outdoor airflow rate.

In Fig. 4, the productivity loss is presented in a thinking task as a function of the quantity of workers in an office space and outdoor airflow rate. The infiltration is 0.1 l/s per m^2 and the contaminant removal effectiveness is 100% (mixing system).

Normally, occupant density is from 0.07–0.3 person/m^2 in offices [26,27]. This means 5–8% loss in productivity with the minimum outdoor airflow rate of 1.0 l/s per m^2. On the other hand, spaces like classroom where the density of pupils is high like 0.5 person/m^2, it is only possible to maintain low sensory pollution load and keep productivity loss low (less than 6%) with outdoor airflow rate 3 l/s per m^2 or over.

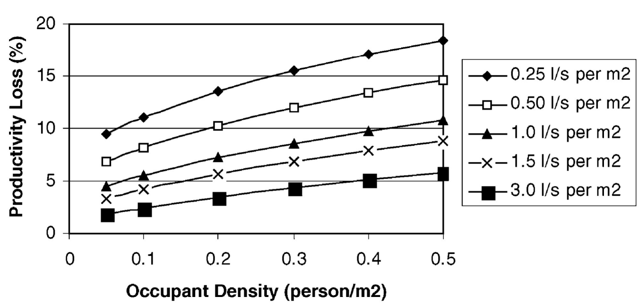

Fig. 4. Productivity loss as a function of quantity of people with different outdoor air supply rates in a thinking task.

5. Ventilation efficiency impact on productivity

Ventilation efficiency has been classically divided into two groups: one for ability of a system to exchange the air in the room and one for the ability of a system to remove contaminants [23]. In this study, the average air contaminant removal effectiveness in the occupied zone is used to estimate the effect of the ventilation system on the productivity loss.

The contaminant removal effectiveness is a measure of how efficiently the air-borne contaminants are removed from the room. Theoretically, the maximum value of the contaminant removal effectiveness efficiency is 100% with complete mixing. However, mixing is not perfect in practice and the efficiency is normally less than 100%. Measurements with displacement ventilation have shown much higher values such as 100–200% [23]. This is significant advantage for displacement ventilation to improve productivity in different working places with the same outdoor airflow rate.

Fig. 5 shows the effect of the contaminant removal effectiveness on productivity loss with different airflow rates in a thinking task. In Fig. 5, the infiltration is 0.1 l/s per m^2, material emission 0.1 olf/m^2 and occupant density is 1 person per 10 m^2.

In displacement ventilation, the supply airflow rate is typically 3–6 l/s per m^2. In cold and temperate climates where the heat recovery system is normally used, the supply airflow rate is the same than outdoor airflow rate. In the tropics, the return air is used and the requested outdoor airflow rate is adjusted for the demand of different applications e.g. in offices about 0.5 l/s per m^2.

The effect of contaminant removal effectiveness on productivity loss is about 0.5–2% between ideal mixing (efficiency of 100%) and displacement ventilation (efficiency of 200%) systems if both of these systems have the same airflow rate per m^2.

Even, the productivity loss of 0.5–2% sounds quite small, the economic impact is about the same level as the annual cost of the total air-conditioning system Wood [5]. Salaries of workers in the US office buildings have exceeded the cost of building energy, maintenance, annualized construction and rental by a factor of 100. Thus, even a 1% increase

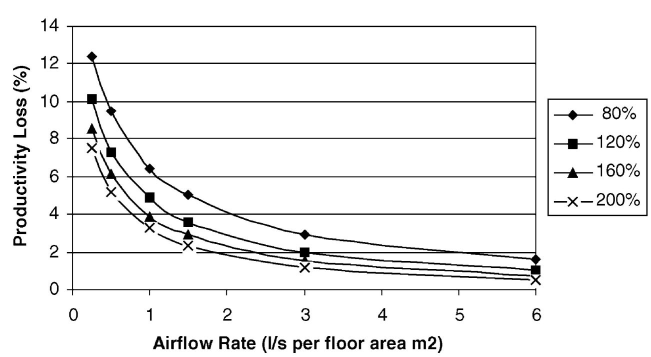

Fig. 5. Productivity loss as a function of the specific outdoor airflow rate with different contaminant removal effectiveness in a thinking task.

in productivity should be sufficient to justify an expenditure equivalent to a doubling of the construction and maintenance costs. It should also be noted that 1–2% reduction in the loss of productivity is equivalent to reduce 5–10% of the proportion dissatisfied.

Fisk and Rosenfeld [4] have estimated in the United States what is the influence of indoor environment on health costs and workers performance. One of the mentioned measure, together with better filtration, to reduce the costs of allergies, asthma and sick building symptoms is increased ventilation. The same effect it is possible to reach by improvement of contaminant removal efficiency.

We can make a crude estimation of the magnitude of productivity and health gains that may be obtained by improving ventilation efficiency using Fisk and Rosenfeld [4] study as a starting point. If we estimate that 10% of the potential annual health related savings is possible to get with improvement of contaminant removal efficiency from 100% (mixing) to 150% (displacement). This could be $100–500 million in costs of allergies. The corresponding annual SBS symptoms increase is of order of $1–2 billion.

Respectively, the estimated productivity loss difference of 0.5–2% between mixing and displacement system could mean $3–12 billion. This estimation includes the assessment that only fourth of people' s work is influenced by indoor environmental improvements. It should be noted that in the previous calculation it is assumed that the ventilation efficiency improvement is contacted in the whole building stock.

6. Inferences from current study

A few interesting issues remained to be resolved in future work:

- The effect of different pollutants on the perceived air quality and needs to be understood better.
- The effect of ventilation efficiency should be investigated on perceived air quality. More detailed work is needed before we are able to estimate the contaminant levels in the breathing zone with different ventilation system.
- Productivity loss for different office tasks must be determined.

7. Conclusion

Task-related performance is significant affected by human perception of indoor air quality. As a general rule, productivity loss due in thinking is more severe than productivity loss in typing. The percent dissatisfied is a good indicator of the productivity loss due to perceived indoor air quality in different office tasks. The proportion dissatisfied may be estimated from acknowledge of pollution loads, fresh airflow rate and ventilation efficiency.

The main factors affecting perceived air quality are pollution load and the outdoor airflow rate. With these main factors and the ventilation efficiency, it is possible to calculate the estimation for the productivity loss in different design conditions. For example, in a case of one person per 10 m^2 (0.1 olf/m^2) and low-emitted material (0.1 olf/m^2), the total sensory pollution load is 0.2 olf/m^2. Normally, the minimum admissible outdoor airflow rate is 0.5–1.5 l/s per m^2 in office spaces. This means that 5–9% productivity loss should be accepted using the minimum airflow rate design method. In a case of 2 persons per 10 m^2 (0.2 olf/m^2) and material emission of 0.2 olf/m^2, the total sensory pollution load will be 0.4 olf/m^2. This leads to 7–13% productivity loss with the minimum outdoor airflow rate. All in all, it should be noted that the usage of minimum-airflow-rate design principle affects always 5–13% on productivity. This productivity reduction is conscious or unconscious development during design process when the outdoor airflow rates are adjusted.

With displacement ventilation, it is possible to improve indoor air quality in a manner that significantly increases productivity compared with traditional mixing system. The effect of the contaminant removal effectiveness on the productivity loss is about 0.5–2% between these systems. The economic impact of 1% productivity loss is equivalent to the annual costs of the total air-conditioning system. Also, it should be noted that 1–2% reduction in the loss of productivity is equivalent to reduction of 5–10% dissatisfied.

We can make a crude estimation of the magnitude of productivity and health gains that may be obtained by improving ventilation efficiency in the US If we estimate that 10% of the potential annual health related savings is possible to get with improvement of contaminant removal efficiency from 100% (mixing) to 150% (displacement). This could be $100–500 million in costs of allergies. The corresponding annual SBS symptoms increase is of order of $1–$2 billion. Respectively, the estimated productivity loss difference of 0.5–2% between mixing and displacement system could mean $3–12 billion. This calculation indicates that the potential financial benefits of improving contaminant removal are huge.

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