Is there an optimum balance between indoor environment, energy consumption and health?

Larsen, T. S.; Rohde, L.; Jensen, R. L.; Larsen, O. K.

Published in:
Journal of Physics: Conference Series

DOI (link to publication from Publisher):
10.1088/1742-6596/2600/14/142006

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Larsen, T. S., Rohde, L., Jensen, R. L., & Larsen, O. K. (2023). Is there an optimum balance between indoor environment, energy consumption and health? *Journal of Physics: Conference Series*, *2600*(14), Article 142006. https://doi.org/10.1088/1742-6596/2600/14/142006

Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Is there an optimum balance between indoor environment, energy consumption and health?

To cite this article: T S Larsen *et al* 2023 *J. Phys.: Conf. Ser.* **2600** 142006

Journal of Physics: Conference Series **2600** (2023) 142006 doi:10.1088/1742-6596/2600/14/142006

Is there an optimum balance between indoor environment, energy consumption and health?

T S Larsen[1*], L Rohde[1], R L Jensen[1], O K Larsen[1]

[1] Aalborg University, Department of the Built Environment, Aalborg, Denmark

*Corresponding author: tsl@build.aau.dk

Abstract. This study investigates the pros and cons of passive strategies in the indoor environment (IE) in relation to energy consumption (EC). It is widely accepted that IE improvements often require energy, particularly for thermal and atmospheric IE. As a result, demands for energy savings might compromise the indoor environmental comfort and health. However, the energy consumption can be reduced by introducing passive measures both regarding temperature and ventilation rates. To investigate this, measurements of temperature and ventilation rates were carried out in eight newly built single-family homes and four renovated single-family homes in a Danish context for three years. The study analyzes the effect of passive cooling using different types of solar shading. The findings show that external solar shading can effectively reduce high temperatures without additional energy consumption for cooling in a Scandinavian context. Also, the difference between mechanical and natural ventilation on CO_2 levels in bedrooms and children's rooms in relation to sleep quality are analysed. Here the results show, that natural ventilation is insufficient to ensure healthy sleeping conditions when it comes to proper ventilation rates and air quality. Supplemental ventilation by either window airing or mechanical aid is necessary.

1. Introduction

From 2020 until today, the world has gone from a worldwide health crisis to a new crisis with the war in Europe and a resulting energy crisis. Both crises have affected how we rate and consider indoor environment (IE) in our buildings. The COVID-19 lockdowns changed how we spent time indoors, using our dwellings 24-7 as workspace, classroom, gym, living space and bedroom. In that period focus on ventilation increased due to an increased focus on health, aiming to reduce COVID-19 transmission. The war in Ukraine, introducing the risk of energy poverty, lead to national energy saving initiatives in many European Countries. Increasing energy prices and, consequently, the need for energy savings, affected the indoor temperatures during summer and winter. During summer, several countries increased the setpoints for AC-systems, often without passive means for reducing temperatures. In the heating season, many countries experimented with lowering the setpoints for heating. For example, in Denmark, all public buildings reduced their setpoints for indoor temperatures to 19°C. Currently, energy savings has a higher priority than thermal comfort.

The two crises have taught us how ventilation is vital for occupant health, and that maintaining comfortable temperatures is costly. An extensive questionnaire survey among 1012 Danish house owners during February and March 2022 (thereby just before the energy prices went up), shows how IE and energy consumption (EC) are prioritized much higher today, than when they bought their homes 20 years ago. 93% rate IE as “important” or “very important” for investing in a house, compared to just

42% when the house was purchased before 2000.[1] This clearly shows a growing demand for good IE among Danish homeowners.

Also, the health aspects of IE concerning sleeping quality are getting higher on the agenda. Hirshkowitz et. al. stated the importance of sufficient sleep in different life stages but also in relation to general health. They state that poor sleeping quality can affect the physical, emotional, and cognitive health, but also the next-day performance is affected after a night with poor sleeping quality. Serious health problems or even compromising health and well-being were reported when large deviations from the recommended range of sleep continued for a longer period. [2] The IE can affect the sleeping quality through thermal conditions [3,4], external noise [5], lighting conditions [6], or indoor air quality [7].

Based on cases found in Danish single-family houses, this paper will give examples of how passive measures can reduce high temperatures without additional EC for cooling and how important additional ventilation in sleeping rooms is to ensure healthy sleeping conditions.

2. Methodology

Indoor environment and energy consumption are closely connected. Improvements in IE, especially within thermal and atmospheric IE, often require energy, and requirements for energy savings can often compromise the indoor environmental quality. However, energy consumption can also be reduced by the introduction of passive measures both regarding temperature and ventilation rates. This study will consider the pros and cons of passive strategies in the indoor environment.

For this study, measurements of temperature and ventilation rates are carried out in eight newly built single-family homes and four renovated single-family homes. The new houses are all built with mechanical ventilation (MV). The renovated houses had no MV before renovation, and only one had MV after renovation. The study is made in a Danish context and was carried out over three years, with measurements before and after renovation. Measurements in the 12 houses were made every five minutes for indoor temperatures, relative humidities and CO_2 levels in kitchens, living rooms, bedrooms, bathrooms and nurseries. In addition, the energy consumption for heating, production of hot water and electricity consumption for ventilation were measured together with weather data from the area.

2.1. Measurements of temperature

For the study included in this paper, temperature measurements in living rooms during summer (June, July, Aug.) with/without solar shading are used to analyze the effect of passive cooling. The temperatures are classified by category I-IV according to 16798-1, table B.5. [8] The design target for the new houses was cat. II. When the number of hours are analysed, cat. I counts number of hours between 23.5-25.5°C. Cat. II (23.0-26.0°C) hours between 23.0-23.5 and 25.5-26.0° etc.

Two scenarios are analyzed. a.) Measurements are compared for two following summers before and after installation of internal solar shading. b.) Measurements of temperature in living rooms with four different types of solar shading.

Figure 1. Four types of solar shading were analysed: a.) Integrated, b.) Construction as shading, c.) Manual shutters, d.) Patio.

2.2. Measurements of ventilation rates

Measurements of CO_2 levels in bedrooms and children's rooms with and without mechanical ventilation are analyzed to evaluate the effect of mechanical ventilation and consider the CO_2 levels in relation to the specific use of the rooms. Beside this, the measurements from the children's room without mechanical ventilation before and after renovation are analyzed to see the effect of increased air tighness. The results are linked to the comprehensive review carried out by Sekhar et.al., who suggest a tentative relationship between bedroom CO_2 levels and sleep quality: [9]

<750 ppm	undisturbed sleep quality range
750-1,150 ppm	possibly disturbed sleep quality
1,150-2,600 ppm	disturbed sleep quality range
>2,600 ppm	disturbed sleep quality range, possibly reduced next-day cognitive performance

3. Results

3.1. The impact of passive cooling strategies on thermal comfort

For the evaluation of passive cooling effects in the 12 houses, two different cases are included in this study. The results are described in the following sections.

3.1.1. Indoor thermal comfort before and after installation of internal solar shading

The first case is measurements from the same house during two summers, see Figure 2. Measurements are made in the living room with east, south and west facing windows. The first summer (Figure 2a) neither internal nor external solar shading were applied except for the narrow external overhang towards south (Figure 2c). The following summer internal solar shading was applied (Figure 2b).

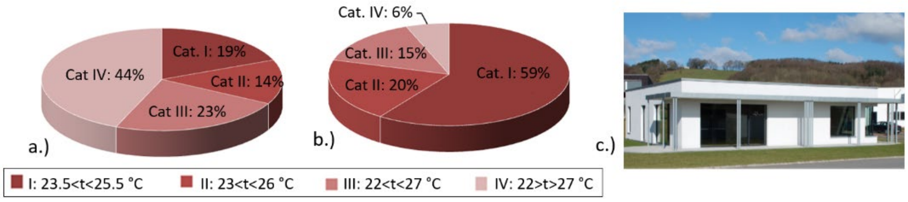

Figure 2. Measurement of living room temperature in two following summer seasons. a.) No solar shading. b.) Internal shading. c.) Southern façade, all windows facing south are part of the living room.

The results show a significant reduction in temperatures above 26°C. Going from to fulfilling the design criteria 33% of the time during the summer without solar shading to 79% the following summer where solar shading was applied.

3.1.2. Indoor temperatures with different types of external solar shading

The second case in this study was carried out to compare different types of external solar shading. Four different types are included in the study, see Figure 3.

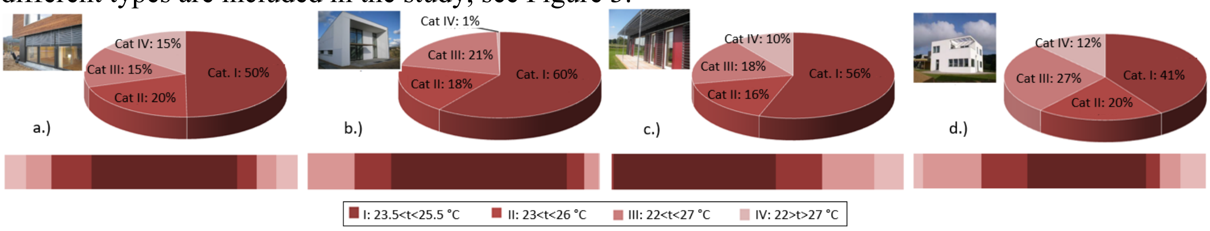

Figure 3. Measurements of living room temperatures with various types of external solar shading. The bar below each figure shows the distribution of the deviations from cat. I, e.g. the part of the bar to the left of cat. I is temperatures below 23.5°C and the part of the bar to the right of cat. I is above 25.5°C.

The cases shown in Figure 3 show a significant potential for energy savings in a Scandinavian context by introducing solar shading. Even internal shading, which often is the cheapest solution, reduces the number of hours above 26°C during the summer from 67% to 21% of the time in the case building in Figure 2. Based on the cases in this study, the highest efficiency of external shadings is found in case a.) with building-integrated external solar shading, which completely blocks out the sun when active, and b.) the deep building construction with large overhangs made by the building construction. It is important to notice that a significant part of the temperatures registered in cat. III og IV are temperatures

 2600 (2023) 142006 doi:10.1088/1742-6596/2600/14/142006

below 23.5° (see Figure 3a and b) and thereby, not temperatures which lead to overheating. When comparing the two solutions regarding other parameters than overheating, the daylight aspect is important to remember since solution b reduces the amount of daylight in the living room all year round compared to solution a, which only reduces daylight when activated. Solution c has approximately the same distribution between the categories, but has an increased number of hours above 25.5°C. The solar shading is manually adjusted shutters combined with a partly transparent overhang. The manual adjustment depends on the users and thereby is the effect of c also highly related to user behavior. Often, these types of shutters are not activated before the users feel the increased temperature in the room, which lowers the efficiency. To accomplish the best results with these types of solar shadings, the users need to learn to activate them before the sun hits the windows, e.g. before going to work in the morning to avoid a warm living room when returning home.

3.2. *Ventilation rates and the link to sleep quality*
The COVID-19 epidemic changed the way and the time we spend at home. The increased number of persons at home, combined with an increased number of hours at home, increase the pollution load in the IE and, thereby, the demand for ventilation. The critical cases will mainly be found within homes without mechanical ventilation, where natural ventilation is insufficient and requires supplemental, active use/window openings, which is often minimized during the heating season.

3.2.1. *Natural air change rates before and after renovation*
During the renovation, air leakages were reduced to reduce the energy consumption. Blowerdoor tests were carried out before and after renovation in the renovated houses. For the case included in this study, the air change rate with a 50 Pa blowerdoor test went from 2.67 to 2.13 l/s pr m^2 heated floor area, corresponding to a 20% reduction. The reduction in air leakage directly affected the ventilation rate in the house, which was measured by the CO_2 levels, see Figure 4.

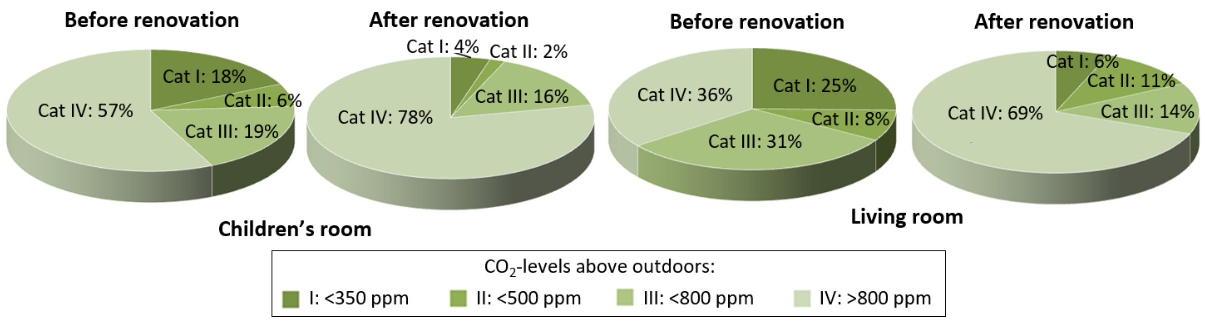

Figure 4. Measured CO_2 levels during two following winters (Dec, Jan, Feb) before and after renovation in children's room and living room.

The air quality was significantly reduced after renovation, showing that occupant behavior needs to be addressed to increase the manual airing of the house. Natural ventilation simply by infiltration is not enough (neither before nor after renovation). The importance of simple guidelines regarding airing twice every day is necessary to help the occupants improve the air quality in the house. Increased airing will most probably also increase the sleeping quality, and thereby the health aspects, for the occupants.

3.2.2. *Comparison of sleeping rooms with and without mechanical ventilation*
In the four renovated houses, one house had mechanical ventilation installed after renovation. Figure 5 shows measurements of CO_2 levels during the winter season (Dec, Jan, Feb) from both a renovated house with natural ventilation (NV) and a renovated house with mechanical ventilation (MV).

 IOP Publishing
2600 (2023) 142006 doi:10.1088/1742-6596/2600/14/142006

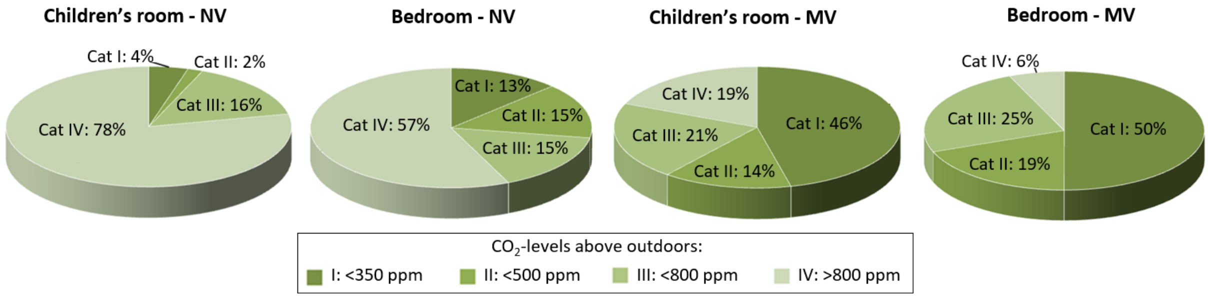

Figure 5. Measured CO_2 levels in natural (NV) and mechanical (MV) ventilated sleeping rooms during winter (Dec, Jan, Feb).

The measurements with and without mechanical ventilation in bedrooms and children's rooms show, for both cases, a large number of hours with CO_2 levels above 750 ppm (= >350 ppm above outdoors). 750 ppm is the maximum acceptable value for "undisturbed sleep quality range" suggested by Sekhar et al. [9]. The best results are obtained in the MV bedroom, where the value is <750 ppm for 50% of the time. However, the bedroom is only expected to be used during the night, and the low values are registered during the daytime (see Figure 6). In the naturally ventilated house, values above 1150 ppm (Cat. IV) are found a large part of the time. CO_2 levels this high will, according to Sekhar et al., disturb sleep quality range. To investigate how high the CO_2 levels become, data from the NV house is shown in Figure 6.

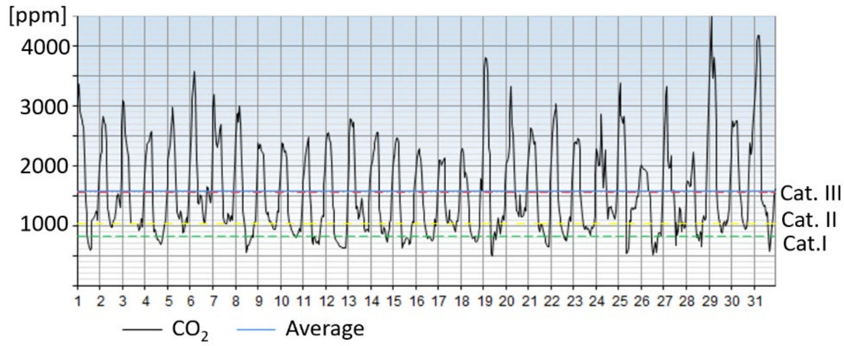

Figure 6. Measurement of CO_2 levels during a winter month in a naturally ventilated children's room.

Figure 6 shows values up to 4500 ppm. The average value in the room for the shown month is 1600 ppm. 18 nights out of 31, the values are above 2600 ppm; thereby, the child sleeping in the room will be at risk of both disturbed sleep quality range and possibly reduced next-day cognitive performance. The data analyses show the same pattern for all sleeping rooms. However, the children's rooms show the worst results since these rooms have a longer occupation time, often starting in the afternoon.

4. Discussion and conclusion

The recent crisis of COVID-19, and the energy crisis following shortly after, have significantly impacted how we consider the importance of indoor environment and energy consumption in our buildings. As more people spend extended periods indoors, the significance of ventilation for maintaining health has become increasingly important. However, the energy crisis has also affected the typical setpoints for indoor temperatures during summer and winter, with energy savings taking higher priority over thermal comfort.

The study presented in this paper examines the benefits and drawbacks of passive measures for improving indoor environment and reducing energy consumption. The measurements of temperature show how passive measures can effectively reduce high temperatures without additional energy consumption for cooling. The cases are taken from a Scandinavian Context, but also warmer climates will be able to benefit from passive cooling, even though it often will be as an energy saving supplement to mechanical cooling.

Measurements of ventilation rates and comparison of natural and mechanical ventilated sleeping rooms show, that the passive solution with natural ventilation is insufficient to ensure healthy sleeping conditions when it comes to proper ventilation rates and air quality. Supplemental ventilation by either window airing or mechanical aid is necessary.

The final question to be asked is now, how to balance the need for energy savings against our indoor environmental comfort and health. When it comes to comfort, compromises are fairly easy to advocate. But when it comes to health, the answer is not as simple, since the derivative effects come with a price.

Acknowledgements

The results presented in this paper are based on the projects "Demonstration of energy use and indoor environment in 10 Danish passive houses" and "EnergiParcel – new energy for your home" supported by Realdania.

References

[1] Rohde L, Larsen T, Knudsen H, Sørensen M, Witterseh T, Vanhoutteghem L, Sonne H, Paturson T, Milsgaard M, Angelo P, Guglietti A, Christoffersen J, Foldbjerg P and Beko G 2022 *IEQ in single family homes - further development of IEQ-compass. BUILD Report 2022:**39*** (Copenhagen)

[2] Hirshkowitz M, Whiton K, Albert S M, Alessi C, Bruni O, DonCarlos L, Hazen N, Herman J, Katz E S, Kheirandish-Gozal L, Neubauer D N, O'Donnell A E, Ohayon M, Peever J, Rawding R, Sachdeva R C, Setters B, Vitiello M V., Ware J C and Adams Hillard P J 2015 National Sleep Foundation's sleep time duration recommendations: methodology and results summary *Sleep Health* **1** 40–3

[3] Zhou X, Lian Z and Lan L 2013 Experimental study on a bedside personalized ventilation system for improving sleep comfort and quality *Indoor and Built Environment* **23** 313–23

[4] Zhang N, Cao B and Zhu Y 2018 Indoor environment and sleep quality: A research based on online survey and field study *Build Environ* **137** 198–207

[5] Chen Y, Hansell A L, Clark S N and Cai Y S 2022 Environmental noise and health in low-middle-income-countries: A systematic review of epidemiological evidence

[6] Wen P, Tan F, Wu M, Cai Q, Xu R, Zhang X, Wang Y, Saddique M, Khan A, Chen W and Hu X 2021 The effects of different bedroom light environments in the evening on adolescents *Build Environ* **206** 108321

[7] Mishra A K, van Ruitenbeek A M, Loomans M G L C and Kort H S M 2018 Window/door opening-mediated bedroom ventilation and its impact on sleep quality of healthy, young adults *Indoor Air* **28** 339–51

[8] Danish Standard 2019 *DS/EN 16798-1:2019 Energy performance of buildings - Ventilation for buildings - Part 1* (Denmark)

[9] Sekhar C, Akimoto M, Fan X, Bivolarova M, Liao C, Lan L and Wargocki P 2020 Bedroom ventilation: Review of existing evidence and current standards *Build Environ* **184**