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Thermal comfort, IAQ and Energy use in Bedrooms

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ABSTRACT

The research question of this report is "Is it possible to save energy by lowering the bedroom temperatures in winter". In this paper first the literature on optimum sleeping temperatures is investigated. Then bedroom temperatures and CO2 levels in a cold week in March 2018 are investigated in 16 bedrooms of students of the Master course Technoledge Climate Desing in 2017-2018 of the faculty of Architecture and the Built Environment of the Delft University of Technology. This study shows that it must be possible to save energy by lowering the bedroom temperature in winter. The measured indoor temperatures were much higher than the 16-18°C recommended by several authors, and with appropriate bed covering and bed clothing could be much lower than 18°C and a period of lower temperatures could be more healthy. The thermal sensation of the occupants also suggest that lower temperatures are possible as more occupant perceive the indoor temperature as slightly warm or warm then slightly cool or cold, even when the outside temperatures are below 10 °C.
The amount of energy that can be saved depends on the 'home' climate of the occupants, with occupants with a warmer 'home' climate preferring higher temperatures. The amount of energy that can be saved also depends on the energy label of the building. A better energy label means that there is less energy necessary to heat the room.
A better scheduling or control system might supply healthier and lower temperatures as night due to a longer time that the heating is turned of. Opening windows to lower the indoor temperature, which might have health benefits, was not preferred by the students because the room would cool down to much, due to safety concerns or due to noise from outside.

KEYWORDS

Thermal Comfort, Bedroom, IAQ, Energy, Netherlands

1 INTRODUCTION

Thermal comfort in bedrooms during sleeping is important to get a good night's rest. Lack of sleep can have an adverse effect on our physical and mental wellbeing. Aspects such as indoor air temperature, indoor air quality and relative humidity need to be researched and extensively studied to understand their relation and impact on the sleep temperature and indoor environment.
As we become more aware of the depletion of our natural sources and increased pollution, methods of saving energy also become necessary. Passive housing concepts are feasible high-performance standards that allow energy use to be substantially reduced without requiring compromises in terms of indoor climate (Berge et al., 2016). Stronger trends towards better insulation standards in new homes and energy efficient retrofitting of old homes with incidence of warmer bedrooms is of concern (Lan et al., 2017). The hypothesis is that the current temperature in bedrooms can be lowered to still comply with regulations and comfort but with a lesser energy demand.
Lower air temperatures are often correlated with lower CO2 levels (Mishra at al. 2018, Lei et al, 2017), which in turn indicate a better indoor air quality. Mishra et al. found that a lower CO2 concentration also leads to more deep sleep and Lei et al. found an increase in mental state at lower CO2 concentrations.

The research question of this report is then **"Is it possible to save energy by lowering the bedroom temperatures in winter".** In this paper first the literature on optimum sleeping temperatures is investigated. Then bedroom temperatures and CO_2 levels in a cold week in March 2018 are investigated in 16 bedrooms of students of the Master course Technoledge Climate Desing in 2017-2018 of the faculty of Architecture and the Built Environment of the Delft University of Technology. Finally the bedroom temperatures are related to the advised bedroom temperatures in the literature and possible energy savings are discussed.
Sleep quality is not taken into account in this research as the test persons were students who we did not wish to impose a strict living regime while they were studying so that a correlation between sleep quality and temperature could not be investigated.

2 LITERATURE

2.1 Optimum sleeping temperature

The WHO (1988) advices that a bedroom temperature of 18 °C can be reached when the outdoor temperature is 0 °C, see figure 1. Many people have, however, taken this temperature as the minimum bedroom temperature, as cited for example by Lan et al.. The Chartered Institution of Building Services Engineers CIBSE (2015) advices a bedroom temperature in winter of 17-19 °C with a clothing of 2.5 clo.

- A report published by the Institute of Housing and The Royal Institute of British Architects [121] recommends that the heating system be capable of raising internal temperatures to the following levels when the outside temperature is 0°C:

Living areas	21°C
Kitchen and circulation areas	16°C
Bathrooms	21°C
Bedrooms	18°C

Figure 1: WHO report (WHO, 1988)

VanderPitte (2006) found that daily averaged indoor temperatures in bedrooms of 39 dwellings in Belgium were 16 °C on average at an ambient outside temperature of 0 °C. The minimum and maximum values at an outside temperature of 0 °C were 8 and 24 °C. Based on these measurements, Peters (Peters et al., 2009) developed an adaptive comfort band for thermal comfort for heating conditions:

$$Tn = 16\,℃ \text{ for } T_{e,ref} < 0\,℃$$
$$Tn = 0.23 \cdot T_{e,ref} + 16 \text{ for } 0\,℃ \leq T_{e,ref} \leq 12.6\,℃$$

On the other hand, sleeping bag manufacturers are designing sleeping bags for sleeping at ambient temperatures as low as -10 °C (Huang, 2008) which means that the minimum temperature for the bedroom is not necessary related to the minimum ambient temperatures for sleeping as long as the bedding system insulates enough.
Lan et al. (2017) wrote a review paper on thermal environment and sleep quality. They found a large range of different bedroom temperatures under which people were comfortable with the exception of very low temperatures below -20 °C. They concluded that there is not yet a consensus on the optimal bedroom temperature under heating conditions, and that the bed climate, controlling clothing and/or bed covering, plays a vital role in the sleeping thermal comfort. Mishra et al. (2016) concluded that sleep quality, as evidenced by EEG

measurements, was not found to be statistically different for bedroom temperatures of 10, 21.1 and 32.2 °C.
From the literature it is therefore concluded that much lower bedroom temperatures than 16 or 18 °C are acceptable. In addition, van Marken Lichtenbelt et al. (2017) pose the hypothesis that "temporally exposure to (mild) heat and cold improves our metabolic health". Thermal comfort may therefore not be the only parameter that should determine the temperature in a bedroom.

2.2 Optimum indoor air quality

The ASHRAE standard recommends a concentration of 700 ppm of CO_2 above the outdoor levels which is usually lays around 300 ppm. A level of 1000 - 1200 ppm is regarded as an acceptable indoor CO_2 concentration (Lei et al., 2017). The value of 1200 ppm is generally used as the healthy reference value in the Netherlands (Bouwbesluit, 2012). Mishra et al. (2017) found that CO_2 levels around 717 ppm led to deeper sleep, but this can also be caused by the corresponding lower air temperature in the bedrooms.

3 METHOD

In this research the bedroom temperatures and CO_2 levels in a cold week in March 2018 are investigated in 16 bedrooms of students of the Master course Technoledge Climate Design of the faculty of Architecture and the Built Environment of the Delft University of Technology in 2017-2018. For more insight into the student's characteristics, thermal comfort preferences, ventilation habits, and the built environments, an online questionnaire was applied. Students received a brief instruction on filling in this form. The questionnaire had to be filled it in the day after the students had the CO_2 and temperature measuring device in their room so that the information received from the questionnaire could be correlated to the CO_2 and temperature measurements.

3.1 Questionnaire

The questionnaire consisted of three sections. The first section contained general questions on occupants' background (age, gender, previous home climate, personal thermal preference at the faculty of Architecture), The question about the previous home climate consisted of asking the occupants to identify the region they had lived in for the past five years on the Köppen-Geiger climate classification map, see figure 2. This question was asked because Amin et al (2016) found that the resident's "home" climate impacts the average indoor temperature. The regions on the maps were divided into a warm and cold climatic region. The warm climatic regions (AW, CWA,CSA and CFA) consisted of all areas which experienced a temperature of 22 ℃ or higher for a period of one or more months in a year. The cold climatic regions (CFC, CFB and BSK) contained the remainder areas which also have at least one months an average temperature below 0 ℃.
In order to understand the personal thermal preference of the occupants the Faculty of Architecture and the Built Environment was considered as a measuring standard. This building was chosen because all the occupants are familiar with the building and spend a lot of time there.
The second part of the questionnaire contained questions about the occupants' built environment. The occupants were asked to look up the energy label of their room on the website www.zoekuwenergielabel.nl. This is an online platform setup by the Dutch government listing out the energy labels of 5 million Dutch residences indicating how energy efficient a home is. They also had to supply the floor area of the room, the orientation of the room, the way the room is heated and ventilated and the type of floor covering. As all

occupants are students of the department of architecture and the built environment they were also asked to draw detailed sketches of the plan and elevation of their bedroom so their built environment could be understood better. While the study focuses on finding out whether **it is possible to save energy by lowering the bedroom temperatures in winter** it was assumed that most occupants live in studio apartments with an open plan setting. The occupants were asked to fill in the other activities they used their bedrooms for throughout the day as it was expected that the activities would have a direct impact on the bedroom thermal environment.

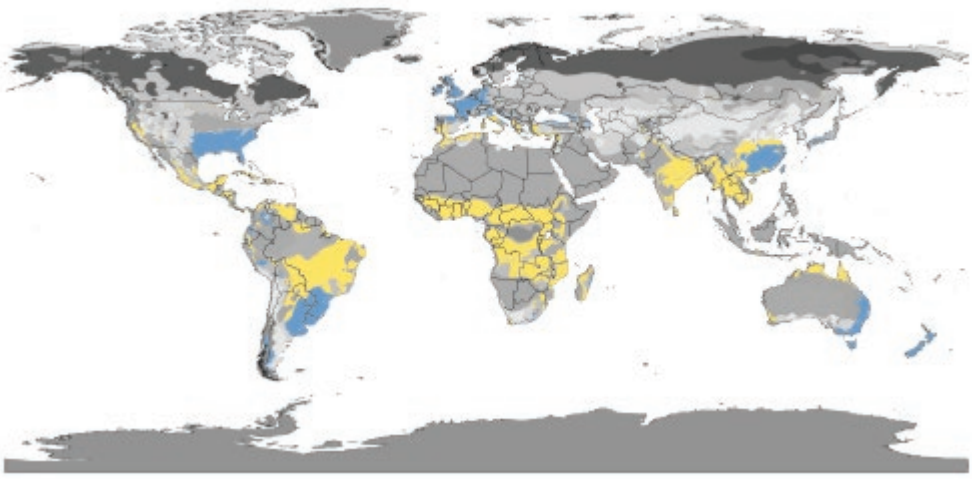

Figure 2: Köppen-Geiger climate classification, blue indicates the cold climate regions and yellow indicates the warm climatic regions.

The third part of the questionnaire consisted of questions on thermal comfort (falling asleep, being asleep, waking up in the middle of the night and waking up). The clo value was asked where a clo value table was supplied. The use of an electric blanket, hot water bottle, the ventilation grill, operable window and radiation was asked too. There was also a question about sleep quality, asking how easy it was to wake up in the morning and how easy it was to fall asleep at night.

3.2 Measurements

Figure 3, Measuring devices, left the I-buttons and right the HOBO device

This study used two types of measuring devices, see figure 3. I-buttons were used to record the bedroom temperature for 2 weeks at 10 minute intervals. A HOBO CO2 meter, which also measures the indoor air temperature and relative humidity was used for one or two nights with a 10 minute intervals.

The devices used for the questionnaire were tested before the measurement to see if they showed big differences in recording the temperature. Then these measurement devices were handed out to sixteen occupants and placed in their bedrooms. These occupants were all students of the masters course Technoledge Climate Design. There were sixteen (not consecutively numbered) I-buttons which were placed in the room for about two weeks to measure the air temperature and two HOBO devices placed in the room for about one or two nights to measure the air temperature, CO_2 levels and Relative Humidity. They were both placed on a desk or table near the bed so the devices would be at about the same height and position in all the rooms. Occupant numbers were consistent with the I-button numbers that were handed out .
The accuracy of I-buttons is about ±1 ℃. The temperature resolution is 0.125 ℃. The I-buttons were placed together at the same time in three locations. Generally, the precision is considered reliable because the average deviation, standard deviation, relative mean deviation and relative standard deviation were small. For the HOBO device, the accuracy of temperature, relative humidity, CO 2 are ±0.21 ℃ , ±4.5%, ±50 ppm. So we regard the tolerances of these two device as ±0.42 ℃ , ±9%, ±100 ppm. When they were together in the same room, only the maximum temperature difference was big, which may be because the initial temperatures in these two devices were different.

4 RESULTS

4.1 Questionnaire

The results from the questionnaire were recorded and are shown below in table 1.14 out of 16 occupants filled in the online questionnaire. Of the 14 occupants ten are female and four are male, all falling within the age group of 20-30 years. One occupant reported living with two rabbits while the rest of the occupants did not house any pets in their bedrooms.
57% occupants come from a cold 'home' climate while 43% came from a warm 'home' climate. There is, which was not expected, no significant correlation between the 'home' climate and the experienced temperature at BKcity (faculty of Architecture). This could be a matter of adaptation to the BKcity climate, or the fact that only 1 person thought that is was warm at the faculty and therefore not all thermal categories were present so that a correlation analysis is not possible.
The results showed that four occupants lived in a house having energy label A, three lived in a house with an energy label of B , five lived in a house with energy label D, and one lived in a house marked energy label G. The building age is significantly correlated to building energy label and is therefore not reported in this paper.
22% of occupants used their bedroom for studying, 14% occupants used it for relaxing, 14% used it for studying and relaxing while 50% occupants used their rooms for cooking, studying and relaxing.
Although sleep quality is not taken into account in this research, the students were asked how easily they woke up. More than half of the students had trouble waking up. When the students were asked why it was so difficult to wake up, their main reason was that they had to work so hard for their studies.

Table 1: Results of the Questionnaire

Question	category	Total (n)
Personal		
Gender	Male	4
	Female	10
Age	20-30	14
Pets	No	13

	Yes	2 rabbits
Main living climate past 5 year	Warm	6
	cold	8
General feeling BK City	Warm	1
	Neutral	7
	Cold	6
Building Environment		
Building label	A	4
	B	3
	D	5
	G	1
	unknown after renovation	1
heating system	scaled radiator	11
	floor heating	3
Ventilation system	natural (vents/grills)	11
	mechanical	2
activities	only sleeping	0
	others (studying, relaxing, cooking,)	14
Comfort		
Can you set a thermostat	No	10
	Yes	4
Do you open the window while sleeping	No	11
	Yes	3
How easily do you wake up	Very Easy	2
	Quite Easy	2
	Quite Difficult	4
	Very Difficult	4

4.2 Measurements

The measurements took place from March 6th till 19th 2018. The time periods were further categorized into when the occupant went to sleep (11:00 p.m. - 1:00 a.m.), during the middle of the night (3:00 a.m. - 4:00 a.m.) and the time period when the occupants woke up (7:00 a.m. - 8:00 a.m.). The results from the HOBO devices and the I-buttons were studied to understand the air temperature, CO 2 content and relative humidity in the bedroom.

4.2.1. Ventilation of the bedroom

The CO_2 levels in only two rooms go above 1100 ppm at night. The occupants explained in the questionnaire that they did not open any windows or ventilation grilles before sleeping. There was no correlation between the bedroom temperature and the CO_2 concentration. This is mainly because the CO_2 concentrations are already good in most cases but also in the two cases where the CO_2 concentration increased to above 1200 ppm the temperature did not rise significantly.

4.2.2. Air temperature of the bedroom

During the time period 11:00 p.m. to 1:00 a.m. two occupants had an average bedroom temperature of 19-21 ℃, six occupants had an average temperature of 21-23 ℃, three occupants had an average temperature of 23-25 ℃ and one occupant had an average temperature of 25-26 ℃. In the middle of the night (3:00 a.m. to 4:00 a.m.) three occupants had an average bedroom temperature of 19-21 ℃, two occupants had an average temperature of 21-23 ℃, seven occupants had an average temperature of 23-25 ℃. In the morning during the time period 7:00 a.m. - 8:00 a.m. three occupants had an average bedroom temperature of

19-21 °C, two occupants had an average temperature of 21-23 °C, three occupants had an average temperature of 23-25 °C and seven occupants had an average temperature of 25-26 °C.

Table 2: Number of occupants with a certain temperature at several time periods

Temperature (°C)	19-21	21-23	23-25	25-26
23:00-01:00	2	6	3	1
03:00-04:00	3	2	7	0
07:00-08:00	3	2	3	7

The high temperatures correspond to the thermal sensation at at going to sleep, while asleep and while waking up, there were more times that the thermal sensation slightly warm and warm was (16) then slightly cool or cool (7). A lower bedroom temperature should therefore be very well possible and contribute to saving energy.

Table 3: Number of occupants with a certain thermal sensation at several time periods

Thermal Sensation	cool	slightly cool	neutral	slightly warm	warm
23:00-01:00	0	3	5	1	3
03:00-04:00	0	2	5	2	3
07:00-08:00	1	1	3	2	5

As found by Amin et al. (2016), this study also discovered a correlation between the student's 'home' climate and the temperatures in the student rooms. In figure 3 the average temperature during the I-button measurement period is displayed for students with a cold 'home' climate and a 'warm' home climate. The group averages vary significantly with the warm 'home' climate students having a higher average indoor air temperature in the rooms.

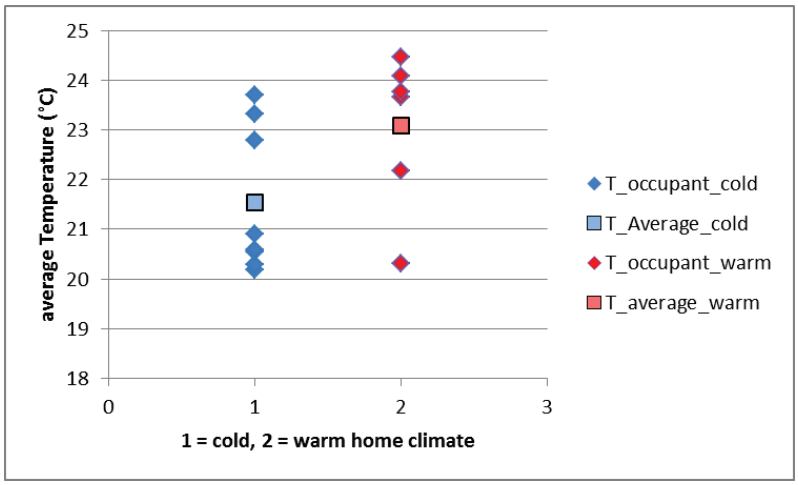

Figure 4, Average bedroom temperatures for cold and warm 'home' climates

The Monicair study (Monicair, 2016) found that Dutch A-labelled dwellings showed in general higher temperatures in A-labelled dwellings than in F-labelled ones. This correlation could not be found in this study, possibly because in this study the warm and cold 'home' climate needed to be distinguished, leaving too little data to draw conclusions.

The TUDelft report 'Selectief Stoken' (Van den Ham, Van der Vliet, 2013) has investigated that a significant amount of energy can be saved by not heating rooms when they are not occupied. They write that this effect depends on the relative decrease of the indoor temperature when the room is not heated. This relative decrease depends on the insulation, ventilation and thermal mass of the room. Buildings with better energy labels have a higher insulation and less unwanted ventilation, and therefore have a lower relative decrease. This effect can also be seen in this study, see the difference between figure 5 and 6.

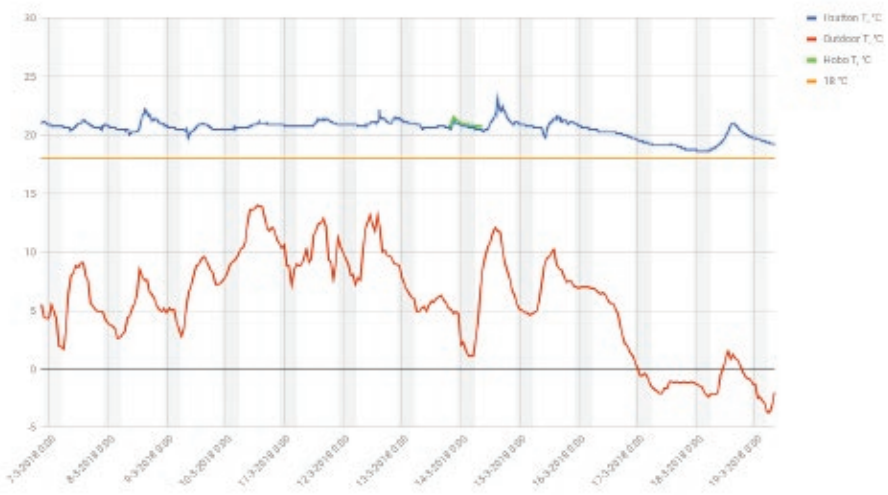

Figure 5, Temperature fluctuation obtained from the bedroom of occupant 10, building energy label A.

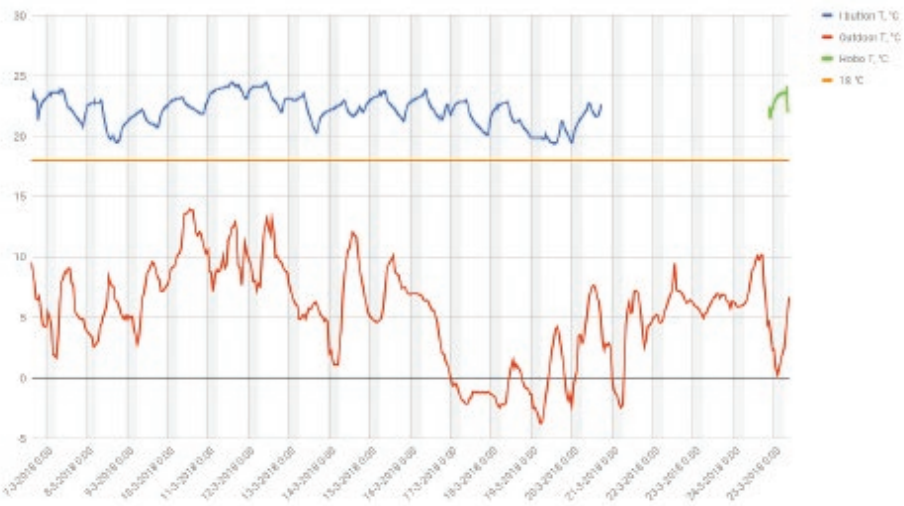

Figure 6, Temperature fluctuations obtained from the bedroom of occupant 18, building energy label D.

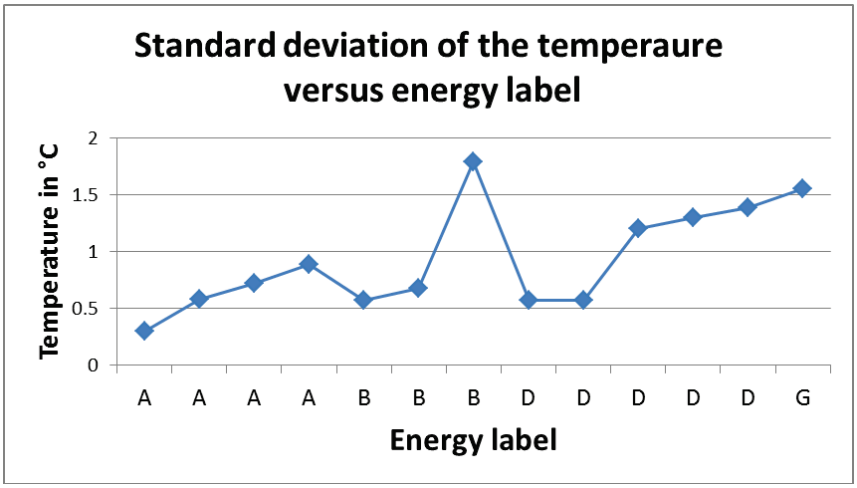

Figure 7: Standard deviation of the temperature versus the energy label

A measure of this relative decrease of the indoor temperature when the room is not heated can be the standard deviation of the indoor temperature, see figure 7. The standard deviation of

the indoor temperature increases with the energy label, except for the one room in a building with energy label B. A closer look at the temperatures of the room with the large standard deviation shows that this occupant opens the window one or two times a day, thereby decreasing the temperature up to 5 ° C for a short time, which has a large effect on the standard deviation.

4.2.3. Controlling the air temperature of the bedroom

Out of the 12 occupants, only 2 reported opening their window every night. There were several reasons why the occupants do not open their windows at night. The main reasons for not opening the window were a. because of the low outside temperature and the subsequent cooling of the room, b. due to safety (living on the ground floor next to a busy road), c. noise from outside. Those that do open the window state that they open the window for fresh air and to reduce the indoor air temperature. Note that it was not very necessary for the indoor air quality, as most of the CO2 levels were well below 1200 ppm.
Besides opening the window, the students have trouble regulation the air temperature of their rooms. 10 occupants could not set a thermostat, although 11 had a scaled radiator. Comments by the students in the questionnaire showed that some were not able to control the heating device in their room to their liking, e.g.: 'the radiator only works when in scale 5' or 'Floor heating is off and still it is always 20 degrees in my room'.

5 CONCLUSIONS

The research question of this report was **"Is it possible to save energy by lowering the bedroom temperatures in winter".** This study shows that it must be possible to save energy by lowering the bedroom temperature in winter. The measured indoor temperatures were much higher than the 16-18°C recommended by several authors, and with appropriate bed covering and bed clothing could be much lower than 18°C. Besides, some authors even conclude that a period of lower temperatures is more healthy. The thermal sensation of the occupants also suggest that lower temperatures are possible as more occupant perceive the indoor temperature as slightly warm or warm then slightly cool or cold, even when the outside temperatures are below 10 °C.
The amount of energy that can be saved depends on the 'home' climate of the occupants, with occupants with a warmer 'home' climate preferring higher temperatures. The amount of energy that can be saved also depends on the energy label of the building. A better energy label means that there is less energy necessary to heat the room.
A better scheduling or control system might supply healthier and lower temperatures as night due to a longer time that the heating is turned of.
Opening windows to lower the indoor temperature, which might have health benefits, was not preferred by the students because the room would cool down to much, due to safety concerns or due to noise from outside.
This research is an exploratory research with only 16 test subjects and where not all parameters were controlled. It was therefore not possible to accurately calculate the possible energy saving when lowering the indoor air temperature. The optimum sleep temperature could also not be determined because of the limited amount of test subjects and the problem that health related aspects could not be investigated without applying for permission for human testing.
This research recommends lower bedroom temperatures in winter. How the lower bedroom temperatures should be obtained in winter is subject of further research. It might be good to have a different heating or ventilation system for bedroom and living room, or even a different amount of insulation for the bedroom.

6 ACKNOWLEDGEMENTS

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