Comfort Assessment of Two nZEBs in Norway

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This work presents the results of a survey and measurement campaign carried on in two wooden buildings in Trondeim, Norway. These are one tower in a student accommodation complex, the Moholt Allmenning, constituted by five CLT towers of 9 floors each, and a mixed CLT-and-timber-frame educational building, the Haukåsen kindergarten. Both buildings comply with the Norwegian Passive house standard and the kindergarten complies with the BREAAM certification as well. Questionnaires focussing on the buildings' users thermal, acoustic, and visual comfort, and on the IAQ were submitted. Measurements of the indoor operative temperature and CO_2 levels were performed. The measurements showed that both buildings are in the NS 15251 Class I with regards to the thermal environment, in both summer and winter. The questionnaires that the perceived dissatisfaction is somewhat higher than that assessed in the measurements, leading to a lower rating, especially in the student housing. One of the most reported issue in the student housing was the noise level, which resulted in 28% of student dissatisfied.

Keywords: Cross Laminated Timber, nearly Zero Energy Buildings, Thermal comfort, IAQ.

Introduction

The present study consists of an analysis of the indoor environmental performance and energy use of two wooden nearly Zero Energy Buildings (nZEB) in Norway. The European Energy Performance of Building Directive (EPBD) recast from 2010 (DIRECTIVE 2010/31/EU) defined nZEB as those buildings witch a high energy performance and large use of renewable energy. In the recast, the definition of the requirements for the buildings' energy performance is left to each of the EU Member State. Such requirements are based on the local climatic conditions and the country-specific method for energy calculations in buildings. Given the different methods used in each Member State for accounting on the energy calculation in buildings, the European Commission issued in 2016 recommendations for the energy performance of NZEBs in different European climatic zones. The benchmarks suggested in the EU 2016/1318 are based on the building's net primary energy use, which is the building's delivered energy multiplied by energy-source-specific conversion factors. The European Commission defined these factors as the primary energy conversion factors and their definition is let to be determined by each of the EU Member State (EU 244/2012). According to the EU 2016/1318 and the ECOFYS report (Hermelink et al. 2013), Norway is placed in the climatic Zone 5 (Nordic), of the five climatic zones defined in the EU. For this climate, the EU 2016/1318 defines the following benchmark for residential and office buildings: between 40 kWh/m^2y and 55 kWh/m^2y, and between 15 kWh/m^2y and 30 kWh/m^2y of net primary energy use for offices and single-family house, respectively.

The use of Cross Laminated Timber is receiving attention in the construction sector in Norway, as it allows to build higher than what is possible with timber frame construction (www.theb1m.com, www.newcivilengineer.com). This allows to densify the urban fabric without sacrificing the envi-

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ronmental benefits in terms of embodied carbon given by wood-based products, as wood building materials have lower environmental impact than that of conventional building materials given their lower embodied energy, and higher recyclability and energy recovery potential (Thormark 2001, Buchanan and Levine 1999, Börjesson and Gustavsson 2000, Dodoo et al. 2009).

Given its "green-material" status, the use of wood in tall buildings was reported to be appreciated by a group of 500 North-American respondents who took part in interviews on people's preference for wood constructions. Majority of respondents declared that tall wood buildings are more visually pleasing, deliver a positive, healthier, more comfortable indoor environment with better air quality (Larasatie et al. 2018). A Norwegian study on employee's preference on the use of wood in hospital showed a clear choice for a partial use of exposed wood surfaces, meaning the most preferred choice was to have two wood surfaces out of five visible surfaces (Nyrud et al. 2014). A study by Burnard et al. on people's preference and perceived naturalness of building materials showed that most of the respondents from Norway, Finland, and Slovenia considered untreated wood surfaces as the most natural materials, and processed wood materials (OSB, MDF and particle boards) were considered as more natural than ceramic, steel, and plastic (Burnard et al 2017).

The scope of this study is to assess the indoor environment of two wooden buildings in Norway, a student housing (Moholt Allmenning) and a kindergarten (Haukåsen barnehage) in Trondheim. Since the design choice of both buildings addressed the extensive use of CLT elements, exposed wood surfaces, and an ambitious energy target, namely Passive House standard, these factors were investigated with respect to their influence on the perceived comfort. This paper is part of a larger study on the cost reduction in wooden NZEB in the European Nordic countries, named NERO (https://neroproject.net).

Method

Case studies

The Moholt Allmenning (www.arkitektur.no/moholt-5050) consists of five towers of 9 floors each. Each floor accommodates 15 resident units for a total of 632 units plus fitness centre, hairdresser, shared laundry. The new complex also hosts a kindergarten for 171 children and a public library. The student rooms are with private bathrooms and organized in a Y-shape around the common area/kitchen/dining area, as shown in Fig. 1 and 2. The building efficiency solutions were designed to comply with the Norwegian Passive House standard NS 3700, as shown in Table 1. External walls are made of 100-mm-thick Cross Laminated Timber (CLT) panels with 200-mm-thick

Fig. 1

Photo of the reference space. (1) exposed CLT panel, (2) linoleum floor, (3) ventilation shaft

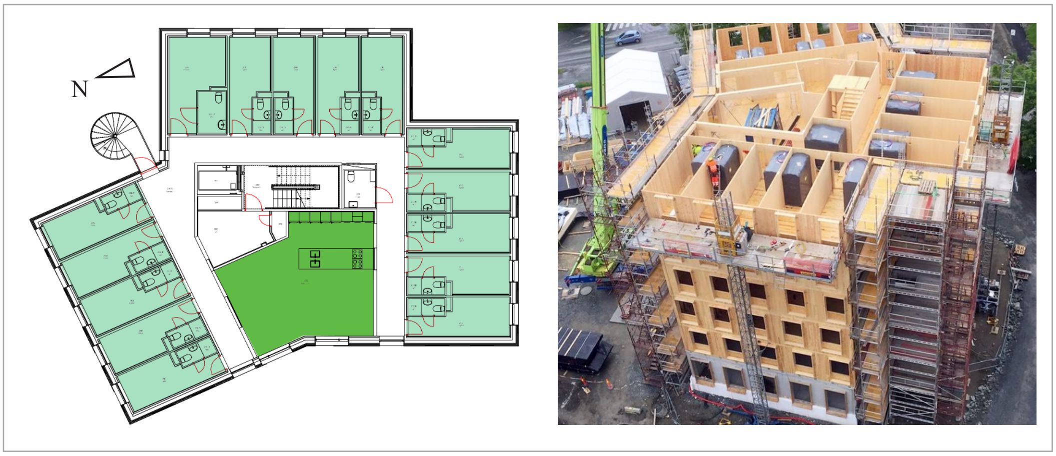

Fig. 2

Left: typical floor plan of Moholt Allmenning, Tower B. In dark green the living area, in light green the students' private rooms. Rooms number 1-5 on the left side, 6-10 on the top side, and 11-15 on the right side of the floor plan. (reference room for the measurements: living area).Right: One of the tower under construction (photo Thomas Bekkavik)

mineral wool insulation. Internal floors are made of 140-mm-thick CLT panels with sound-proof insulation below the flooring layer. The five towers, kindergarten, and library are connected to a ground-source heat pump with a total production capacity of 2.2 GWh/year. The residential towers have mechanical balanced ventilation in the students' rooms and in the living area with 85%-efficiency air heat recovery units. The ventilation supply is controlled by the CO_2 sensors installed, and the flow of the air volume is controlled by the air extracts in the kitchens.

The Haukåsen kindergarten (www.arkitektur.no/haukasen-barnehage) was first in its building type to be assessed according to the BREEAM-NOR standard, being classified BREAAM Very Good. The kindergarten has a compact design, being developed on two floors mainly East and West oriented, and it was planned to minimize the corridor area, as shown in Fig. 3. The building currently serves places for 54 children and 11 employees in a floor area of 950 m^2. The construction was built according to the Norwegian passive house requirements set in the NS 3700 standard. To reach the U-value of 0.09 W/m^2K of the external walls, a 400-mm-thick insulation layer was installed in the façade timber frame. Moreover, the vertical posts of the timber frame are composed of two 100-mm-thick timber elements bound together with a 100-mm-thick polyurethane rigid foam (MDI) to reduce the thermal bridges. A 500-mm-thick mineral wool insulation in the roof allowed the structure to reach the designed U-value of 0.09 W/m^2K. The floor and the internal wall construction are made of CLT elements (Fig. 4). The flooring was laid on a steel railing system, which was mounted on the CLT elements, with a sound insulation layer below the railing. A 50-kW ground-source heat pump connected with 6m^2 of solar thermal collectors serve the domestic hot water need, the water-based radiators, and the heating coils in the HVAC system. The ventilation system is controlled by CO_2 sensors, the motion-detectors, and the temperature sensors placed in the buildings. The ventilation system is equipped with an air-heat recovery unit with an efficiency of 84%.

Fig. 3

First floor of the Haukåsen kindergarten. In light green the children activity area. In dark green the reference rooms for the measurements

Fig. 4

Photo of the reference room on the ground floor. (1) perforated sound-proofing OSB, (2) exposed CLT panel, (3) wood-fiber ceiling panel, (4) linoleum floor, (5) ventilation shaft

Fig. 5

Photo of the reference room on the first floor. (1) perforated sound-proofing OSB, (2) exposed CLT panel, (3) wood-fiber ceiling panel, (4) linoleum floor, (5) ventilation shaft

Table 1

Characteristics of building envelope of the two case studies

	Moholt Allmenning, Tower B.	Haukåsen kindergarten
Exterior walls	0.13 W/(m^2 K)	0.09 W/(m^2 K)
Roof	0.10 W/(m^2 K)	0.09 W/(m^2 K)
Ground floor	0.17 W/(m^2 K)	0.08 W/(m^2 K)
Windows	0.80 W/(m^2 K)	0.80 W/(m^2 K)
Window g-value	0.55	0.37
Doors	0.80 W/(m^2 K)	0.80 W/(m^2 K)
Measured air tightness q_{50}	0.3 m^3/h	0.14 m^3/h

The delivered energy use of the Moholt Allmenning, Tower B, was retrieved from the building management system and it was 80 kWh/m^2 in 2017, which included the electricity for space heating, ventilation, pumps, fans, lighting, and appliances. The delivered energy use of the Haukåsen kindergarten was retrieved from the online building management system, which is used by the Trondheim Municipality to survey in real time the energy use of several Municipality-owned buildings. The measured energy use was 46 kWh/m^2 in 2017, which included the delivered electricity for space heating, ventilation, pumps, fans, lighting, and appliances. The currently enforced Norwegian standard that defines the method for energy calculations in buildings (NS 3031/2014) does not include a national definition for primary energy use, as the energy calculation is based on the delivered energy to the building. Therefore, not being possible to compare the delivered energy of both the Moholt Allmenning and the Haukåsen kindergarten to a Norwegian nZEB benchmark, the latest Norwegian energy code for buildings (Byggteknisk forskrift TEK17) is used. The Molholt Allmenning and the Haukåsen kindergarten use less energy than the limits defined in the Tek17 and these are 95 kWh/m^{2}y and 135 kWh/m^{2}y for residential buildings and kindergarten, respectively. Both buildings are in the energy-class A, according to the energy classification in Norway (www.energimerking.no).

Measurements and questionnaires

Onsite measurements of indoor air temperature (dry and wet bulb), relative humidity, CO_2 level, and air velocity were taken during different days in January and February 2018 for the heating season, and in August and September 2018 for the cooling season. The measurements were performed with portable instruments connected to a data logger. During the measurement campaign, the instruments were placed at different heights from the ground, as recommended in the ISO 7726, and these are 0.1 m, 0.6 m, and 1.1 m for a seated person, for measuring the radiant and air temperature, and the air velocity at the ankle, abdomen, and head level, respectively. Given that the student apartments are all identical in the Moholt Allmenning towers, an apartment located at the 4th floor of the Tower B was chosen as the representative space. It was not possible to get access to the students' own rooms for the measurements, therefore the living area was used (dark green area in Fig. 2). The measurements in the Haukåsen kindergarten were taken in the common area at the first floor, and in the classroom in the ground floor (dark green areas in Fig. 3). The operative temperature shown in the result section is calculated as follows:

$$t_{op} = \frac{t_r + \left(t_a \cdot \sqrt{10 \cdot v_a}\right)}{1 + \sqrt{10 \cdot v_a}} \quad (1)$$

Where t_r is the radiant temperature, t_a is the dry bulb air temperature, and v_a is the air velocity. In February 2018, a survey on the users' satisfaction of the indoor environment in both buildings was sent to the 632 students of the Moholt Allmenning and to the 11 employees of the Haukåsen kindergarten. The survey consisted of an anonymous online questionnaire where the informants were asked to rate their perceived thermal sensation, IAQ, noise level, and illuminance satisfaction, for a total of 11 questions, of which 8 were rating-scale question-types, and 3 were open questions. The perceived thermal sensation was assessed according to both the 7-points rating scale (from *hot* to *cold*) and the 4-acceptability rating scale (from *clearly acceptable* to *clearly unacceptable*). The IAQ, the noise intensity, and the daylight level were assessed according to the 4-acceptability rating scale, and the odour intensity according to the 7-points rating scale (from *no odour* to *overpowering odour*), as described in the NS 15251.

Results

Moholt Allmenning Tower B

Fig. 6 shows the results of the winter (February 2018) and summer (July-August 2018) measurements in the reference room, with superimposed the temperature band according to a Class I residential building (C1 max = 25.5˚C and C1 min = 21.0˚C) defined in the NS 15251.The average operative temperature is 22.8˚C in winter (max 24.2˚C and min 21.6˚C), which is very close to the average Class I comfort temperature (C1 average = 23.3˚C). The summer average operative temperature is 21.8˚C (max 23.5˚C and min 21.1˚C), which is within the Class I temperature band.

Therefore, the reference room complies with the EN 15251 Class I with respect to the thermal environment, in both summer and winter, as shown in Fig. 6. The measured average CO_2 level is 410 ppm in winter and 355 ppm in summer, which were both within the Class I IAQ range (min 350 ppm, max 500 ppm) for all the measurement time in winter, and in summer, as shown in Fig. 6. The measurement of the relative humidity gives an average of 22% in winter (RH_{max} = 31% and RH_{min} = 17%), and 52% in summer (RH_{max} = 61% and RH_{min} = 34%).

The questionnaire was answered by 173 students (58% female, 41% male). As shown in Table 2, the number of students living in the rooms adjacent to the common area and the kitchen was larger than those living in the room next to the corridor. This uneven distribution of the respondents may have an influence on the reported comfort level, specifically that regarding the noise and odor intensity. The results show that 88% of the respondents rated their thermal sensation between slightly warm and slightly cold, which includes a 53% of students who gave a neutral thermal sensation. More respondents chose the *warm* rating (10%) than the *cool* rating (2%). The thermal environment was rated as acceptable by 92% of the total respondents. Both questions on the perceived air quality and odour intensity (not shown in the table) scored 75% of acceptability. With regard to the IAQ in the students' rooms, heavy, stuffy and poor air was mentioned in 39% of the answers, good and fresh air in 24% of the answers, and the need to open the window or the door for better ventilation was reported in 15% of the answers. The perceived noise intensity was rated as acceptable by 72% of the respondents. Most of the noise source was attributed to the common area (Fig. 1 and 2) and the floor above, 35% and 28% of the total answers, respectively. Noise from the floor below scored 16%, from the other rooms scored 9%, and from outdoor 12%. The daylight quality was rated as acceptable by 92% of the respondents (not shown in Table 2). The results of the questionnaire are summarized in Table 4, where the total acceptability level is calculated by adding the *clearly acceptable* and *just acceptable* answers from the questionnaires.

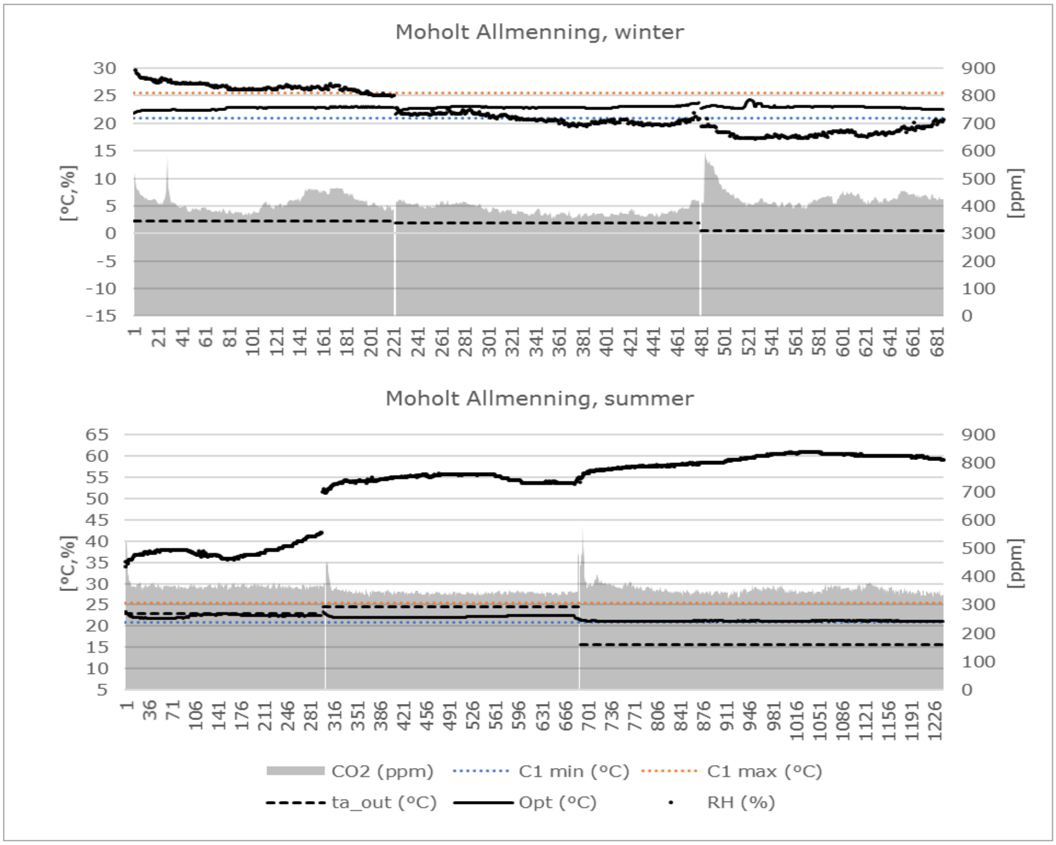

Fig. 6

Top and bottom: winter and summer measurements in the reference room. *C1 min* and *C1 max* are Class I building max and min comfort temperatures, *ta_out* is the outdoor temperature, *Opt* is the operative temperature, *RH* is the relative humidity

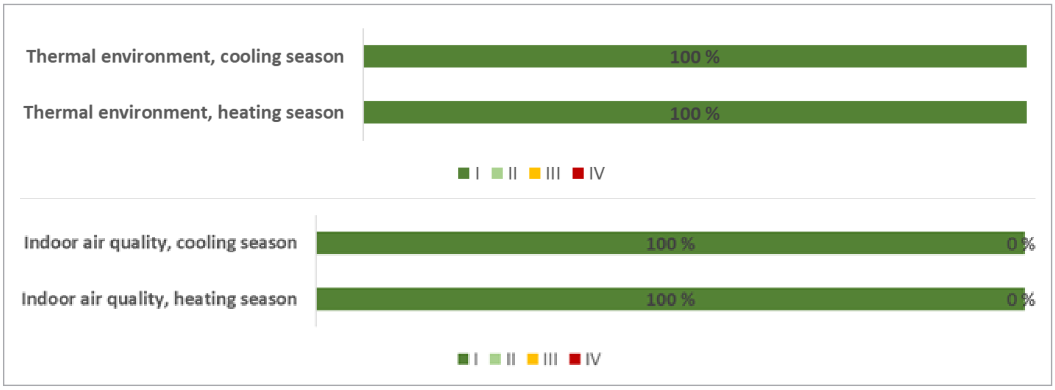

Fig. 7

Percentage of the measurement time in which the reference room of the Moholt Allmenning lies in the different building Classes according to the EN 15251, from Class I in dark green to Class IV in red

Table 2

Answers from the questionnaire in the Moholt Allmenning

Moholt Allmenning (173 respondents)	All respondents	Male respondents	Female respondents
Room number 1-5	34 %	12 %	22 %
Room number 6-10	29 %	12 %	17 %
Room number 11-15	36 %	17 %	19 %
Thermal sensation: hot	0 %	0 %	0 %
Thermal sensation: warm	10 %	3 %	6 %
Thermal sensation: slightly warm	17 %	9 %	9 %
Thermal sensation: neutral	53 %	22 %	31 %
Thermal sensation: slightly cool	17 %	7 %	10 %
Thermal sensation: cool	2 %	0 %	2 %
Thermal sensation: cold	0 %	0 %	0 %
Perceived temperature: clearly acceptable	63 %	27 %	36 %
Perceived temperature: just acceptable	29 %	12 %	17 %
Perceived temperature: just unacceptable	7 %	2 %	5 %
Perceived temperature: clearly unacceptable	1 %	1 %	0 %
Perceived IAQ: clearly acceptable	42 %	15 %	27 %
Perceived IAQ: just acceptable	34 %	15 %	18 %
Perceived IAQ: just unacceptable	21 %	8 %	13 %
Perceived IAQ: clearly unacceptable	3 %	3 %	1 %
Perceived noise intensity: clearly acceptable	34 %	16 %	18 %
Perceived noise intensity: just acceptable	38 %	14 %	24 %
Perceived noise intensity: just unacceptable	24 %	10 %	14 %
Perceived noise intensity: clearly unacceptable	4 %	2 %	2 %
Noise source: common area	35 %	-	-
Noise source: floor above	28 %	-	-
Noise source: floor below	16 %	-	-
Noise source: other rooms	9 %	-	-
Noise source: outdoor	12 %	-	-
IAQ: fresh	13 %	-	-
IAQ: good/OK	11 %	-	-
IAQ: heavy/stuffy	37 %	-	-
IAQ: dry	17 %	-	-
IAQ: damp	5 %	-	-
IAQ: poor	2 %	-	-
IAQ: need to open window/door	15 %	-	-

Haukåsen kindergarten

Fig. 8 shows the results of the winter (February 2018) and summer (September 2018) measurements in the reference rooms (Fig. 3 and 4), with superimposed the temperature band according to a Class I kindergarten (C1 max = 24.5˚C and C1 min = 19.0˚C) defined in the NS 15251.The average operative temperature is 21.0˚C in winter (max 22.1˚C and min 18.3˚C), which is close to the Class I average comfort temperature (21.8˚C). Similarly, the summer average operative temperature is 21.0˚C (max 22.9˚C and min 20.3˚C). Therefore, the thermal environment in the reference rooms comply with the EN 15251 Class I for almost all the measurement time in winter, and for 100% of the measurement time in summer, as shown in Fig. 9. The measured average CO_2 level is 497 ppm in winter and 395 ppm in summer, and these were both in compliance with the Class I IAQ range (min 350 ppm, max 500 ppm). The IAQ lied within Class II for 5% of the measurement time in winter, and it was in Class I for 94% of the time in summer (Fig. 9). The measurement of the relative humidity gives an average of 21% in winter (RH_{max} = 26% and RH_{min} = 15%), and 46% in summer (RH_{max} = 59% and RH_{min} = 33%).

The questionnaire was answered by all the 11 employees of the Haukåsen kindergarten. The results show that the employees are evenly distributed in the building in the classrooms on the ground (45%) and first floor (45%), as shown in Table 3. The indoor temperature was rated as neutral by 60% of the respondents, and 90% of the respondents answered within the range *slightly cool – slightly warm*, which corresponds to the combined rating of *acceptable* and *just acceptable*. The IAQ was rated as acceptable by 80% of the respondents, and the noise intensity was rated as acceptable by 90% of the respondents. Most of the noise source was reported to occur in the same working room (56%) or in adjacent rooms (33%). Only 11% (equals to one person) reported noise from the floor above. It is worth noting that given the noisy environment in which most of the em-

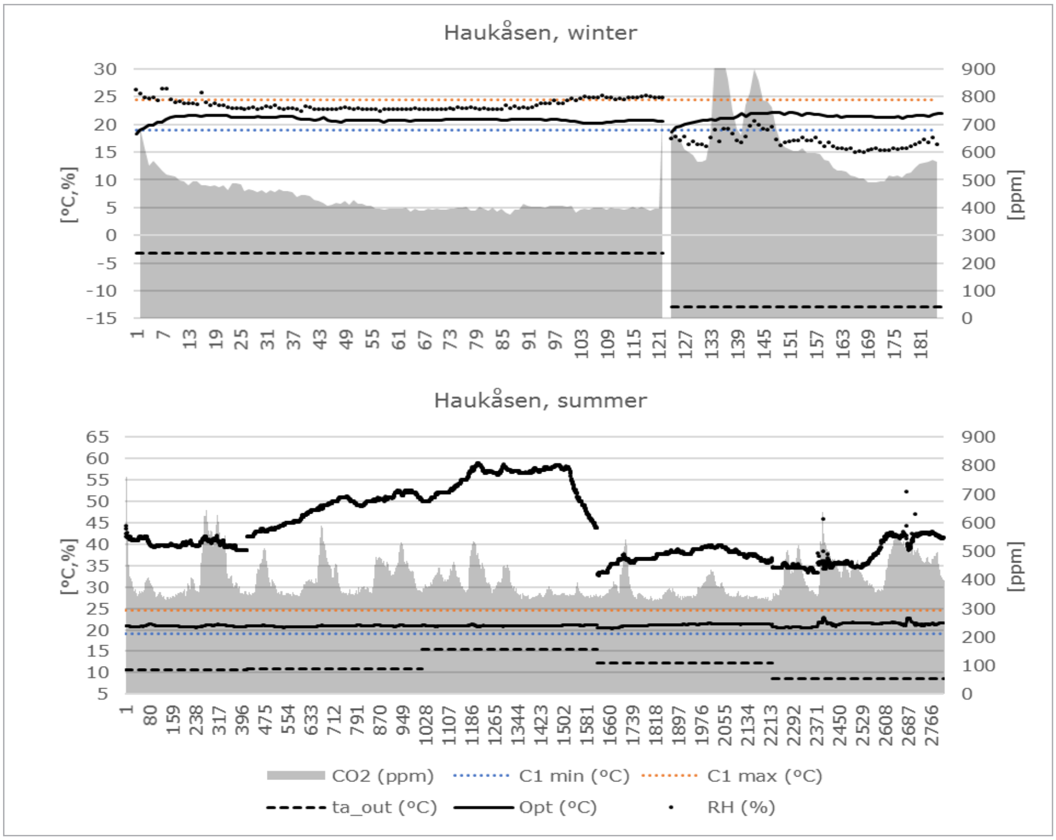

Fig. 8

Top and bottom: winter and summer measurements in the reference room. *C1 min* and *C1 max* are Class I building max and min comfort temperatures, *ta_out* is the outdoor temperature, *Opt* is the operative temperature, *RH* is the relative humidity ployees work, noise coming from other rooms/floor is less likely to be noticed. Regarding the IAQ, less than half (44%) of the answers fresh and good IAQ was mentioned, while dry air was reported in 31% of the answers, and poor and stuffy air in 26%. Regarding the perceived odour intensity (not shown in Table 3), 80% of the respondents rated no odours, and 20% of the respondents answered either weak or moderate odour intensity. All the respondents are satisfied with the daylight quality and 90% of them rated it as *just right*, while the remaining 10% rated it as *bright*. The results of the questionnaire are summarized in Table 4, where the total acceptability level is calculated by adding the *clearly acceptable* and *just acceptable* answers from the questionnaires.

Haukåsen kindergarten (11 respondents)		Perceived IAQ: just acceptable	10 %
Classrooms on ground floor	45 %	Perceived IAQ: just unacceptable	10 %
Office on first floor	10 %	Perceived IAQ: clearly unacceptable	10 %
Classrooms on first floor	45 %	Perceived noise intensity: clearly acceptable	45 %
Thermal sensation: hot	0 %	Perceived noise intensity: just acceptable	45 %
Thermal sensation: warm	0 %	Perceived noise intensity: just unacceptable	9 %
Thermal sensation: slightly warm	9 %	Perceived noise intensity: clearly unacceptable	0 %
Thermal sensation: neutral	64 %	Noise source: your work room	56 %
Thermal sensation: slightly cool	18 %	Noise source: other rooms on the same floor	33 %
Thermal sensation: cool	9 %	Noise source: other rooms on the floor above	11 %
Thermal sensation: cold	0 %	Noise source: other rooms on the floor below	0 %
Perceived temperature: clearly acceptable	70 %	IAQ: dry	31 %
Perceived temperature: just acceptable	20 %	IAQ: stuffy	13 %
Perceived temperature: just unacceptable	10 %	IAQ: poor	13 %
Perceived temperature: clearly unacceptable	0 %	IAQ: OK/good/fresh	44 %
Perceived IAQ: clearly acceptable	70 %		

Table 3

Answers from the questionnaire in the Haukåsen kindergarten

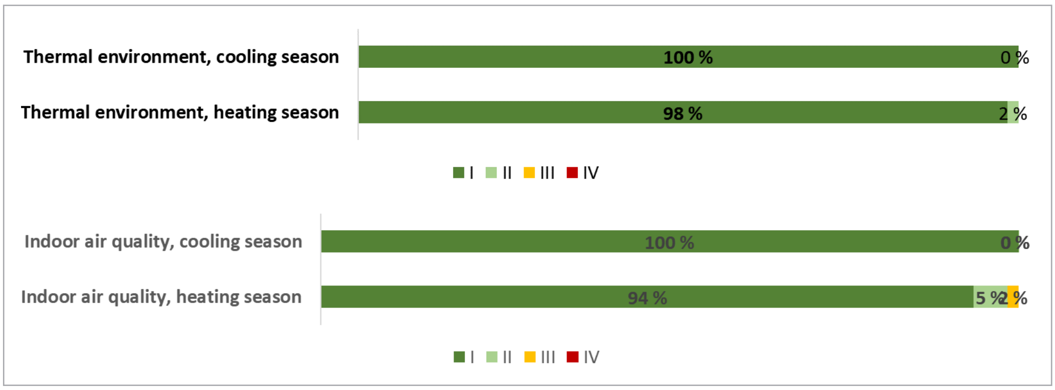

Fig. 9

Percentage of the measurement time in which the reference rooms of the Haukåsen kindergarten lies in the different building Classes according to the EN 15251, from Class I in dark green to Class IV in red

	Moholt Allmenning	Haukåsen kindergarten
People finding the **overall indoor environment** acceptable	81%	90%
People finding the **thermal environment** acceptable	92%	90%
People finding the **indoor air quality** acceptable	76%	80%
People finding the **illuminance level** acceptable	92%	100%
People finding the **acoustic level** acceptable	72%	91%
People finding the **odour intensity** acceptable	76%	90%

Table 4

Summary of the questionnaires

Discussion and Limitations

Several limitations are to be considered in this study. Since it was not possible to access the students' own rooms in the Moholt Allmenning, the results of the questionnaire do not reflect the measurements taken in the common area. Therefore, the obtained classification of both the thermal environment and the IAQ are to be applied to the common area only. It is worth noting that from the results of the questionnaire the overall dissatisfaction with the thermal environment was between 8% and 12%, when either the 7-points scale or the 4-points scale are used, respectively. This places the students' rooms at the border between the Building category II and III. The rating of satisfaction (75%) with the IAQ places the students' rooms in the Building category III. Since a difference is evident between the measured data and the results of the questionnaires, new measurements in several students' rooms should be performed to assess if these are consistent with the students' rating of the building.

When comparing the results of the questionnaire and the measurements in the Haukåsen kindergarten, the above-mentioned difference is also present. The employees rated the building according to Class II, with respect to both the thermal environment and the IAQ, while the measurement of the operative temperature and the IAQ places the building mainly in Class I. It must be noted that the small number of respondents (11 employees) affects to a large extent the results of the questionnaire, as one sample of the population is enough for changing the building classification. Moreover, during the measurements campaign the authors informally spoke with the employees who reported cold environment in the classroom on the ground floor, even if the measurement did not show significant differences from the temperature registered on the first floor. This may be explained by the different activity level of the employees in the two floors. As toddlers' rooms are on the ground floor, the activity level of the supervisors is mainly sedentary, on the contrary to the activity level of the supervisors on the first floor, where the older children are placed.

A clear difference is shown between the rating of satisfaction given in the structured (acceptability scale-based) answers and that given in the open-field answers. When the respondents were asked to comment on the IAQ, they generally gave a lower acceptability rating than that given in the 4-scale question. The acceptability rating of the IAQ in the Moholt Allemenning was 76% (*clearly acceptable* and *just acceptable* answers) against 24% of answers that mentioned a good IAQ. The reason of such a difference is because in the open-field answers the respondents used multiple adjectives to describe their perceived IAQ, and these were reported as separate records in Tables 2 and 3.

The spikes in the CO_2 level in the measurement in both buildings are due to the initial acclimatization of the sensor, and the spike registered in the winter measurement in the kindergarten is due to the presence of a large number of children next to the sensor. Moreover, the CO_2 sensor needed approximately 20 minutes of acclimatization at the beginning of each measurement, thus recording slightly higher values of CO_2 concentration.

Conclusions

The results of the measurements and survey on the indoor environment of two wooden buildings in Trondheim, Norway were shown in this paper. The buildings are one CLT tower in a student accommodation complex, the Moholt Allmenning, and a mixed CLT-and-timber-frame educational building, the Haukåsen kindergarten. According to the measurements the followings conclusions can be drawn:

- both buildings are in the NS 15251 Class I with regards to the thermal environment, in both summer and winter.
- Both buildings are energy-class A.
- With regard to the IAQ, the Moholt Allmenning complied with Class I during the heating season, and the cooling season. The Haukåsen kindergarten complied with Class I in the cooling season, and mainly (94%) Class I in the heating season.
- The averaged measured CO_2 concentration was below 500 ppm in both buildings.

- According to the questionnaires, the thermal environment was rated acceptable by at least 90% of the respondents. The IAQ was reported as acceptable by 76% and 80% of the respondents in the student housing and the kindergarten, respectively. The most reported issue in the student housing was the noise level, which resulted in 28% of student dissatisfied.
- More measurements are needed in the students' room of the Moholt Allmenning to verify if the dissatisfaction with the IAQ corresponds to high levels of CO_2.

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