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TESTING OF DAYLIGHTING AND HEAT LOAD PARAMETERS IN DIFFERENT DESIGN TYPES OF DAIRY COW HOUSING

Milada BALKOVÁ[1], Jana LENDELOVÁ[2]*, Ingrid KARANDUŠOVSKÁ[2], Miroslav ŽITŇÁK[2]

[1]Slovak Environmental Agency, Banská Bystrica, Slovakia, milada.balkova@sazp.sk
[2]Slovak University of Agriculture in Nitra, Faculty of Engineering, Institute of Agricultural Engineering, Transport and Bioenergetics, Nitra, Slovakia, ingrid.karandusovska@uniag.sk, miroslav.zitnak@uniag.sk
*correspondence: jana.lendelova@uniag.sk

The aim of the work was to test the level of daylight conditions and the heat load of animals in the summer season in two identically oriented dairy barns with different construction and material solutions. Measurements were carried out in the same farm and at the same time. A classic massive building – reconstructed barn (RB) for 158 dairy cows with a volume of 34.3 m^3 per animal supplemented in summer by motor ventilation (522.15 m^3 per animal, total 82,500 $m^3 \cdot h^{-1}$) had an indoor daylight factor *DF* below the limit $DF_{avg,\ int}$ = 0.21% (against the recommended *DF* = 1% for housing dairy cows). In the external feeding alley, which was screened by a shelter and an adjacent building, lighting conditions were compliant with $DF_{avg,\ ext}$ = 4.02%. However, the level of heat load as measured by indices was above the limit ($THI_{avg,\ int}$ = 84.65) despite the motor ventilation used; in the outdoor feeder $THI_{avg,\ ext}$ = 81.63, against the recommended stress-free level *THI* = 72. Similarly, according to the *ETIC* assessment, the results were deficient $ETIC_{avg,\ int}$ = 26.16 and in the outdoor feed $ETIC_{avg,\ ext}$ = 25.24 against the recommended level of *ETIC* = 20. The second building, a new barn (NB) for 444 dairy cows was a new large-cubicle indoor structure with 82.53 m^3 per animal, with a translucent roof (37.87% of the total 4,927.6 m^2 was of translucent polycarbonate triple-pipe roofing). This amount of translucent elements together with large window openings of a total area of 879.6 m^2 was also reflected in the values of the daylight factor $DF_{avg,\ int}$ = 7.59%. The level of heat load was not significantly lower compared to a massive RB with motor ventilation over a double row of bunks (fans with a total capacity of 82,500 $m^3 \cdot h^{-1}$). In NB, no animal cooling features were activated, but technically and spatially they were easily solvable (whether economical ventilation systems with laminar flow, precisely controlled sprinkling of animals, or another combination of evaporative and flow solutions). These efficient types of cooling would be almost impossible to deploy in RB or only with a special renovation of the building, which would be comprehensively costly.

Keywords: daylight factor; thermal index; barn construction

In intensive milk production systems, care must be taken to ensure an appropriate environment throughout the year to animals (Leão et al., 2015). Barns for dairy cows must be designed to promote the maximum animal comfort and mitigate adverse effects of climatic and physical factors (Andrade et al., 2020). Since the structures and materials used for housing dairy cows together with the technological equipment and ventilation system can affect the quality of the environment in the animal zone, their development also needs to be given an appropriate attention (Kic, 2017; Šístková et al., 2010; Pšenka et al., 2018). In the process of understanding the consequences of climate change and developing precision livestock farming, the scientific community has also devoted much attention to the negative impacts of excessive heat load on animals and ways to protect them to ensure their welfare (Li et al., 2020; Herbut et al., 2015; Wang et al., 2018a; Polsky and von Keyseringk, 2017; Dash et al., 2015; Berman, 2005, Herbut and Angrecka, 2018). Studies in recent years have focused on those animal species that have the greatest difficulty in hot weather to dissipate excess heat and whose discomfort due to heat stress is inducing high economic damage (Gantner et al., 2015; Zhou et al., 2022).

In dairy farming, extreme heat stress leads to increased heart rate, reduced feed intake, and consequently reduced production. Heat stress can also have serious health impacts negatively affecting milk quality and reproductive parameters, and it has an overall negative impact on animal behaviour (Zhou et al., 2022; Yan et al., 2021; Imrich et al. 2021; Herbut and Angrecka 2013; Brouček et al., 2020; Bohmanova et al., 2007; Li et al., 2020). Thermal stress in dairy buildings occurs during the arrival and persistence of hot weather with unfavourable temperature-moisture conditions of outside air (Herbut and Angrecka, 2013). In addition, stress can be aggravated by ineffective ventilation and cooling systems, or even a lack of them. An important aspect that is often overlooked is the location of barns and their construction in terms of protection from excessive sunlight (Angrecka et al., 2017; Brouček et al., 2020). According to the temperature-humidity index (*THI*), hot weather is more unsuitable in higher air temperature and higher relative humidity (Armstrong, 1994; Zähner et al., 2004). In a more detailed assessment, for example, according to the equivalent temperature index for dairy cattle (*ETIC*), heat stress is increased by the third parameter (in addition to air temperature and relative humidity), which is solar radiation, and on the contrary, heat stress is reduced by increasing air ventilation velocity (Wang et al., 2018a, b). The variety of construction-technical solutions of stables affects not only the achieved level of improvement of microclimate inside the building, but also the light conditions in the environment of animals and workers. Daylight is one of the main required components of the work environment of people and of the husbandry environment of livestock. The lighting of the animal space is necessary for the biological wellbeing of the organism and is essential for the creation of good animal welfare and the contact with mates from the same species (Rendic, 2002; Hayes, 2007; Polderman et al., 2006, Touitou et al., 2017, Asher et al., 2022). Better lighting and visual contact between cows contribute to building social hierarchy and preventing traumatism. This has forced researchers and producers of agricultural equipment to develop and implement technologies for the best possible lighting and microclimate, thus ensuring optimal husbandry conditions (Penev et al., 2014; Furnaris, et al. 2016). Lighting assessment (such as assessment of accessibility to food and water, quality of food and water, comfort and cleanliness of beds, slip-resistant corridor surfaces, area and spatial parameters of functional zones and stall elements, microclimatic parameters, pollutant content, etc.) is an important part of animal welfare assessment. Sunlight and UV radiation are beneficial for the health of large ruminants and increase their productivity, provided they are not accompanied by extremely high ambient temperatures (Varlyakov, 2010; Penev et al., 2014). Cattle is sensitive to light intensity, usually less than 50 lux is perceived by cows as night (Zejdová et al., 2014). Daytime lighting intensity in the cattle barn should range between 150 and 200 lux. In order to perform work safely and properly and to improve environmental hygiene in barns, favourable working lighting (normally at 200 lux) is required (Papež and Kic, 2015; Wilson et al., 2022; STN EN 12464-1). The aim of this study was to test the indoor microclimatic parameters and daylight conditions in two materially, structurally, and spatially different dairy cow barns.

Material and methods

The study was conducted on a commercial cattle farm (latitude: 50° 17´ 31.24″ N, longitude: 16° 09´ 36.04″ E) consisting of 15 buildings located at an altitude of 287 m above sea level. Microclimate data from two barns of different construction and time of construction were analysed.

The first building – reconstructed barn (RB) for 158 cows was a 50-year-old typified building of solid masonry construction, which was renovated to a three-row structure, and a new external feeding area was also built. The old building was 70 m long and 11.4 m wide (Fig. 1). The height of the building at the ridge was 9.7 m, and the height of the side (longitudinal) walls was 4.3 m. There were 20 window openings in the longitudinal walls of the RB, which were 0.9 m high and 1.2 m wide. In the front walls of the stable, there were 2 doors 2.2 m wide and 3 m high, which were partially closed only in winter. There was a ventilation opening in the roof ridge, 0.5 m wide. Parts of the roof covering were lightened by five 1 m wide transparent polycarbonate strips connecting the ridge to the eaves. The outer roofed feeder was 70 m long and 3.25 m wide. There were 6 door openings (2 × 1.7 m) leading from the stall to the feeder. In the longitudinal axis of the stall, 5 basket fans (each with a capacity of 16,500 $m^3 \cdot h^{-1}$) with a total capacity of 82,500 $m^3 \cdot h^{-1}$ were placed above the double lying cubicles.

The second building – new barn (NB) was for 444 dairy cows. There were eight rows of lying cubicles and two internal feeding corridors. The length of the new barn was 85.4 m, and the width of the barn was 52 m (Fig. 2). The height of the 3-section roof in the ridge was 18.2 m. The steel structure with 4 longitudinal rows of pillars was constructed in a longitudinal module with an axial distance of the pillars of 5 m. The height of the longitudinal wall was 8 m on the south side and 6.5 m on the north side. The roof covering was made of two materials (Fig. 3). Part of the roof covering, located at the longitudinal side walls, was made of polyurethane agropanels (Fig. 3 – covering A), the middle part was made of ondalite two-chambered polycarbonate translucent wave cavity roofing (Fig. 3 – covering B).

The front walls were made of translucent 3-chamber polycarbonate panels.

On the front wall, there were 8 access gates for mechanics made of green plastic roller shutters. Above the concrete longitudinal walls with a height of 2.1 m, there was a roller shutter system 85 m long. The height of the fully opening roller shutter was 5.9 m on the south side and 4.4 m on the north side.

The measurement points in the RB are shown in Fig. 1, with points no. 1, 2, 3, and 4 representing the interior data set (O1) and measurement point no. 5 being included in the exterior dataset (O2). The measurement locations in the new barn (NB) are shown in Figs 2 and 3.

Microclimatic parameters – air temperature (°C), air velocity ($m \cdot s^{-1}$), relative humidity (%), and illuminance –

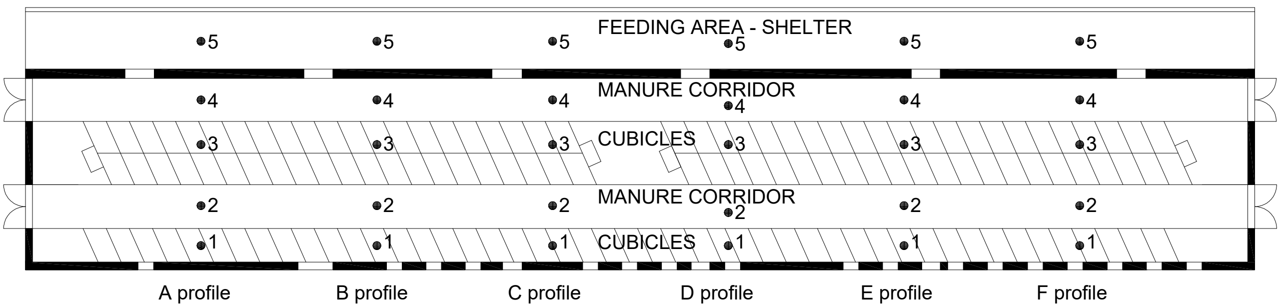

Fig. 1 Layout of the RB with the measurement points of illuminance conditions and microclimate parameters

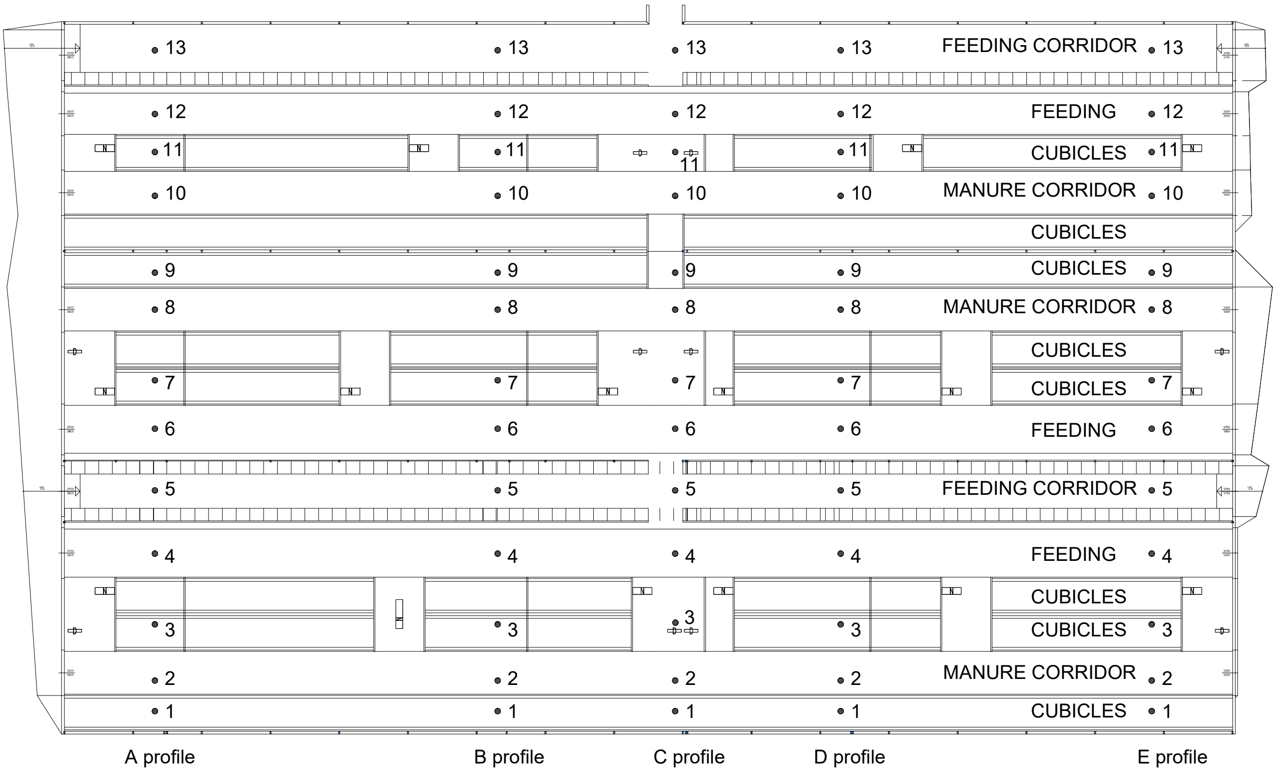

Fig. 2 Layout of the NB with the measurement points of illuminance conditions and microclimate parameters

lighting value (lx) – were measured simultaneously in each stall using ALMEMO instruments.

Measurement points in the NB no. 1, 2, 3, 4, 10, 11, 12, 13 were located under the polyurethane roof (N1), and measurement points no. 5, 6, 7, 8, 9 were located under the translucent polycarbonate roof (N2). The accuracy level of the measurements was 3; the number of repeats of the measurements both indoors and outdoors was 5.

The daylight factor (*DF*) was calculated according to Eq. (1).

$$DF = (\bar{E}/\bar{E}_h) \cdot 100 \ (\%) \tag{1}$$

where: $\bar{E}$ – the average lighting value at a point in a given plane of the interior space (lx); $\bar{E}_h$ – the average outdoor comparative lighting value, measured on an unshaded plane (lx)

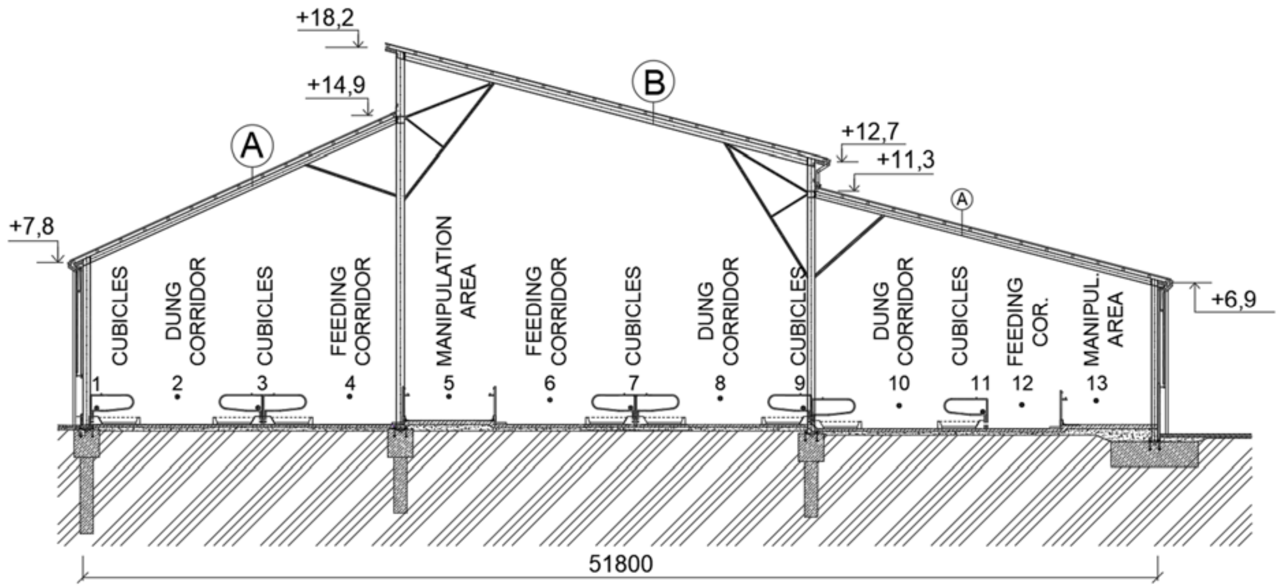

Fig. 3 Cross-section of the NB with lighting and microclimate measurement points (1–13)
A, B – roof configuration; 1–13 – the measurement points of illuminance conditions and microclimate parameters

For free stall housing of dairy cows, the recommended value is D_{min} = 1.0% (according to the original Slovak standard STN 36 0088). The recommended value for service personnel is D_{min} = 1.5%. In terms of microclimate (temperature, humidity), temperature-humidity index *THI* (according to Kelly and Bond, 1971) and equivalent temperature index for dairy cows *ETIC* (according to Wang et al. 2018b; Hempel et al., 2019) were evaluated (Eqs 2, 3).

$$THI = (1.8 \cdot T_{db} + 32) - ((0.55 - 0.0055 \cdot RH) \cdot (1.8 \cdot T_{db} - 26.8)) \quad (2)$$

where: T_{db} – dry bulb temperature (°C); *RH* – relative humidity (%) (Kelly and Bond, 1971)

The following levels were used to evaluate the heat stress of dairy cows: mild heat stress 72 < *THI* < 79, moderate heat stress 80 < *THI* < 89, and severe heat stress *THI* > 89. However, the initial threshold for heat discomfort has been reported by several authors to be lower than 72 (Allen et al., 2015; Nordlund et al., 2019).

$$ETIC = T_{db} - 0.0038 \cdot T_{db} \cdot (100 - RH) - 0.1173 \cdot |WS|^{0.707} \cdot (39.2 - T_{db}) + 1.86 \cdot 10^{-4} \cdot T_{db} \cdot SR \quad (3)$$

where: T_{db} – dry bulb temperature (°C); *RH* – relative humidity (%); *WS* – wind speed ($m \cdot s^{-1}$); *SR* – solar radiation ($W \cdot m^{-2}$) (Wang et al., 2018a)

The following four categories were used for *ETIC* evaluation: mild category 18 ≤ *ETIC* < 20, medium category 20 ≤ *ETIC* < 25, severe category 25 ≤ *ETIC* < 31, and emergency category 31 ≤ *ETIC* (Wang et al., 2018b).

The microclimate indices established by scientific studies reflect numerically the state of the environment, which is qualitatively important for ensuring suitable living conditions for animals. The quality of the working environment of workers was assessed according to Act 355/2007 and Decree 99/2016. Data on microclimatic parameters as well as daylight factors in the old and new stables were processed statistically using one-factor ANOVA. The significance of differences with the level of 0.05 between the mean values of individual parameters in the barns were determined by Tukey's test. All calculations were performed using STATISTICA 7 CZ software.

Results and discussion

The results of evaluation of ambient air temperature measurements and the calculated values of daylight factor (*DF*) in the old building are shown in Fig. 4.

From the calculated values of *DF*, it is clear that in the interior of the old barn (points 1–4 of transverse profiles A–F), *DF* values did not comply with the standard requirements at any point (Table 1). On the contrary, as expected – all the points in the outdoor feedlot complied with the standard requirements. In the area of the beginning and end of the outdoor shelter, the *DF* was six to nine times higher than the minimum required level.

The values of the daylight factor in the interior of the RB (DF_{int}) were insufficient (0.05% < DF_{int} < 0.76%), and no maximum value reached the required threshold of 1%. This was due to the small opening area (total window area was 21.6 m^2, door area

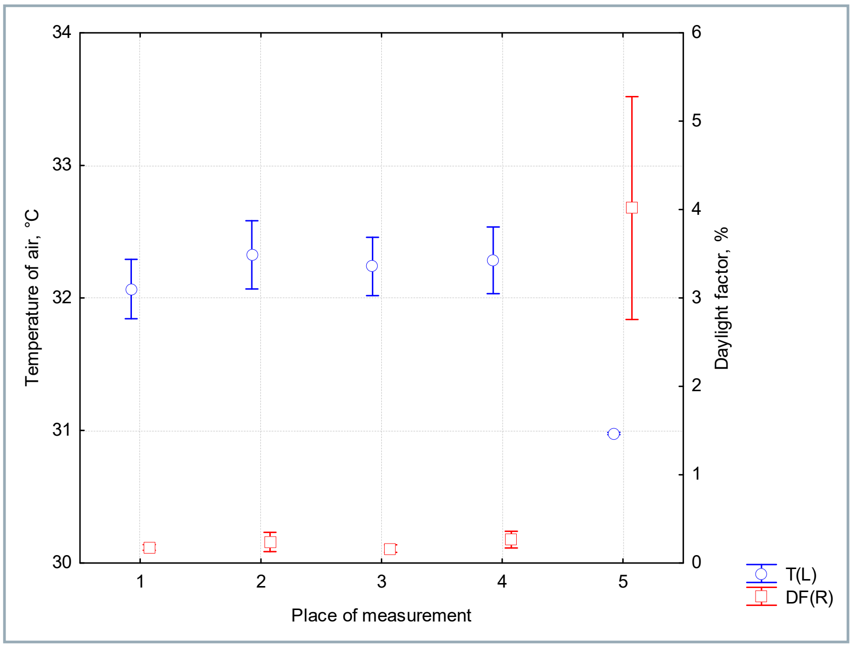

Fig. 4 Results of air temperature and daylight factor in the RB (points 1 to 4 – measurement points located inside the stables, point 5 is located outside)

Table 1 Calculated values of daylight factor (*DF*) in the reconstructed building

Measurement number	A profile *DF* (%)	B profile *DF* (%)	C profile *DF* (%)	D profile *DF* (%)	E profile *DF* (%)	F profile *DF* (%)
1	0.17	0.20	0.12	0.05	0.26	0.26
2	0.76	0.11	0.09	0.05	0.07	0.35
3	0.31	0.12	0.09	0.06	0.10	0.30
4	0.67	0.13	0.12	0.12	0.10	0.45
5	9.2	4.3	1.6	1.6	1.2	6.2

Table 2 Calculated values of *DF* in the new barn

Measurement number	A profile *DF* (%)	B profile *DF* (%)	C profile *DF* (%)	D profile *DF* (%)	E profile *DF* (%)
1	9.58	8.28	6.67	6.01	5.36
2	7.84	6.51	5.67	6.02	5.06
3	7.89	5.10	4.74	5.43	4.37
4	8.16	6.77	6.91	7.22	6.96
5	10.24	10.42	10.68	11.15	8.79
6	11.79	12.67	12.76	13.31	11.0
7	11.49	12.25	12.59	13.12	11.89
8	10.92	10.85	10.48	11.50	11.69
9	8.93	8.31	7.76	7.98	5.73
10	6.60	4.75	4.43	4.96	4.41
11	4.65	2.75	3.0	7.27	3.05
12	5.09	2.78	2.51	8.25	3.61
13	5.51	3.13	3.52	8.89	5.41

64 m^2, roof ridge gap opening 35 m^2). In addition, dirty dark walls contributed to the reduction of daylight in the barn.

The lighting values DF_{ext} of the feed corridor were satisfactory due to the fact that the feeding area was outside the building in an outdoor area covered from above by a bitumen roofing. Here, the values ranged from 1.2% to 9.2%. The lower values under the shelter were in the part that was screened by the neighbouring building. At locations inside the barn, temperatures at each measurement location varied proportionally with *DF* values (Fig. 4). Temperatures in the RB were above 32 °C, while in the shaded part of the shelter, the temperature trend was the opposite. The daylight factor in the new barn exceeded the recommended values in all the points by several times. The spacious large-cubature barn with its transparent roofing and gable walls, as well as the open side walls, made it probable that daylighting in the barn would be satisfactory even under adverse climatic conditions. The calculated values of *DF* (Table 2) ranged from 2.51% to 13.31%.

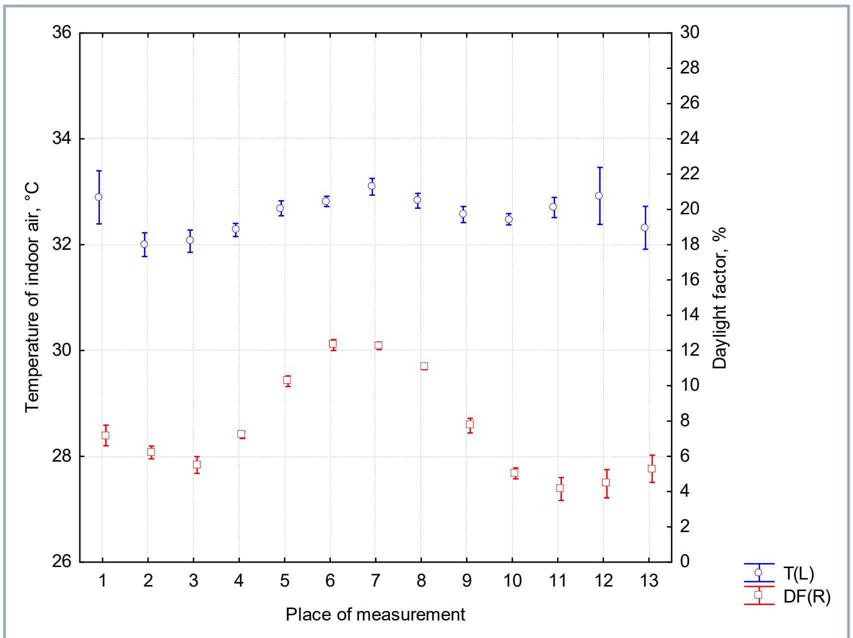

Fig. 5 Results of temperature and *DF* conditions in the NB: points 1, 2, 3, 4, 10, 11, 12, 13 are located under the polyurethane roof (A); points 5, 6, 7, 8, 9 are located under the translucent polycarbonate roof (B)

The results of the evaluation of indoor temperature and daylight factor measurements in the NB are shown in Fig. 5. In all the 65 measurement positions, the requirements for both cattle (DF_{min} = 1%) and caregivers (DF_{min} = 1.5%) were met at T_{ai} >30 °C. The *DF* values that were found at the places under the polyurethane roof (A) and near the high side openings (opening clearance H0 >4 m) along the side walls were comparable to those found under the outer shelter of the old building. However, the *DF* values detected at the central measurement locations, located under the translucent polycarbonate ceiling tiles (B), were significantly higher than those at other edge locations 1, 2, 3, 4, 10, 11, 12, 13 (p <0.05) and reached almost twice the *DF* values compared to the outer shed.

However, significantly higher climatic indices, both *THI* and *ETIC* (p < 0.05), were also found in light-exposed locations, which is also related to slow air transport in the animal zone at the locations most distant from the side window openings. In the locations where *T*-values rise with higher *DF* values in the *NB*, it is reasonable to ventilate the middle part of the barn to remove moisture and also reduce animals' sensible temperature. Days with an influx of humid warm weather are a problem in this area. In such cases, increased air velocity flowing mainly from the side of the adjacent screening building would have a beneficial cooling effect, which would be demonstrated in particular by a reduction in the *ETIC* coefficient. The results of calculations from the measured data of the climate and light parameters *DF*, *T*, *RH*, *THI*, and *ETIC* are summarised in Fig. 6. The temperatures in the shelter are affected by the outside environment, hence no dependence between *DF* and *T* is seen. However, in the *NB*, it is evident that in the part where *DF* values are higher, temperature values and associated *THI* and *ETIC* values are higher despite lower *RH*.

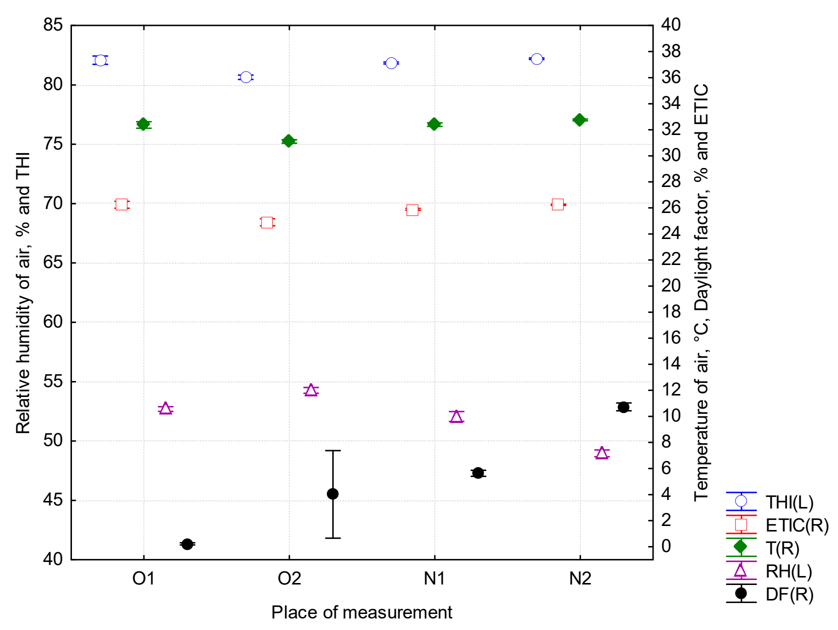

Fig. 6 Results of temperature and humidity measurements and calculations of the indices (*DF*, *THI*, and *ETIC*) in both barns

O1 – average values of measured variables inside the RB (points 1, 2, 3, 4); O2 – average values of measured variables in the outside shelter (feed corridor) of the RB (point 5); N1 – average values of the measured variables in locations near the high side openings located under the non-transparent polyurethane roof in the NB (points 1, 2, 3, 4, 10, 11, 12, 13); N2 – average values of the measured variables in locations under the translucent polycarbonate roof in the NB (points 5, 6, 7, 8, 9)

From the calculations and statistical evaluation of *THI* and *ETIC*, it was found that in all the assessed locations, the environment of the animals was unsatisfactory in terms of heat load, with the threshold values *THI* = 72 and *ETIC* = 20. The best conditions were found in the external feeding area. As no fans were installed in the NB and the average airflow velocity was not demonstrably higher than that in the RB – building with fans ($p > 0.05$), there was no effect of reducing the heat load in zone N1 in terms of *ETIC* assessment according to the calculation method. However, separate attention should be devoted to the assessment of air exchange in the central zone of the NB, where both *THI* and *ETIC* in zone N2 reached the highest values.

The climatic conditions in animals' living zone were very stable and did not show differences ($p > 0.05$) in terms of temperature ratings in N1 and N2. In all other indoor locations, compared to location O2, temperatures were significantly higher than those in the open feeding area under the shelter ($p < 0.05$). However, this difference may be minimised in windless conditions under high solar radiation. The driest area was the central zone, above which there was a large vertical roof opening of 263.5 m^2 (3.1 × 85 m) and a polycarbonate roof slab. Air exchange in this area was also supported by large air gates in the front walls of the building, which were open during hot summer days.

The highest *DF* values were found in zone N2 (*DF* = 10.73%). No difference was found in the peripheral areas of the new barn (N1) compared to the feed shelter of the reconstructed barn (O2), and the average *DF* value in zone N1 was 1.4-times higher than the average *DF* value in zone O2 (N1 = 5.63% > O2 = 4.02%).

Lighting is the third component of the technical provision of indoor microclimate in buildings, along with heating and ventilation. In agriculture, as in other productive activities, good quality lighting contributes to higher labour productivity and better results. It is also one of the most important factors in occupational safety (Hutla, 1998). Buildings used for the keeping of livestock must be constructed according to general technical requirements for buildings in such a way as to ensure a healthy indoor environment and not to threaten the housing and breeding of animals (Pogran et al., 2011). Barn buildings designed in Central Europe in the past often did not meet the environmental quality requirements and the required daylighting of the barn (Kic, 2022; Angrecka et al., 2017). Light transmission features such as windows and skylights were not large enough to provide sufficient daylight. A modern and varied range of new material solutions for stables allows for a significant improvement in the daylighting of indoor spaces, which is an energy-efficient all-year-round solution. The most cost-effective way to improve the indoor climate can be contributed by proper design of natural ventilation, mainly dependent on the opening size, opening location, and the area ratio of inlet-to-outlet openings modellable by modern computational methods (Wu et al., 2012; Rong et al., 2016; Yi et al., 2019) and other ways to eliminate heat stress. In addition, an appropriately supplemented photoperiod as one of the environmental factors can have a positive effect on the production parameters of dairy cows when properly managed (Dahl et al., 2012; Asher et al., 2014). However, it is necessary to ensure that the design of relighting elements also takes into account summer heat extremes, highlighting the risk of limitless increases in *DF* and, if necessary, the necessary compromise optimising the level of summer heat load with an appropriate correction of the level of daylight factor.

Conclusion

In the European climate, dairy cow houses are most exposed to light and heat in the summer months of June, July, and August. On the basis of our measurements in this period, it was found that in the interior of the reconstructed stable of massive type with the interior cubature of 34.3 m^3 per dairy cow and the over-lit roof area of 14.28%, the standard requirements of daylighting (daylighting factor $DF_{avg,\ int}$ = 0.21% instead of the required *DF* = 1% for animals and *DF* = 1.5% for employees) were not fulfilled. In the external feeding area, lighting conditions were satisfactory, with $DF_{avg, ext}$ = 4.02%. In the new large-capacity building of light hall construction with a cubature of 82.5 m^3 per dairy cow, where 37.9% of the roofing consisted of translucent material, the daylight illumination according to *DF* met the specified requirements of both animals and employees (DF_{min} = 2.51% and DF_{max} = 13.31%). Heat load in both buildings was moderate (above the *THI* >80 and *ETIC* >25 thresholds), which in the reconstructed barn with fans gave only few possibilities for more efficient cooling. In contrast, in the large-cubicle new barn without cooling elements installed yet, heat load is technically solvable as these devices can be better utilised both spatially and energetically.

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